Environmental Sustainability of Digitalization in Manufacturing: A Review

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Review

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Abstract: The rapid development and implementation of digitalization in manufacturing has enormous impact on the environment. It is still unclear whether digitalization has positive or negative environmental impact from applications in manufacturing. Therefore, this study aims to discuss the overall implications of digitalization on environmental sustainability through a literature study, within the scope of manufacturing (product design, production, transportation, and customer service). The analysis and categorization of selected articles resulted in two main findings: (1) Digitalization in manufacturing contributes positively to environmental sustainability by increasing resource and information efficiency as a result of applying Industry 4.0 technologies throughout the product lifecycle; (2) the negative environmental burden of digitalization is primarily due to increased resource and energy use, as well as waste and emissions from manufacturing, use, and disposal of the hardware (the technology lifecycle). Based on these findings, a lifecycle perspective is proposed, considering the environmental impacts from both the product and technology lifecycles. This study identified key implications of digitalization on environmental sustainability in manufacturing to increase awareness of both the positive and negative impacts of digitalization and thereby support decision making to invest in new digital technologies.

Keywords: environmental impact; digitalization; Industry 4.0; manufacturing; environmental sustainability; digital technologies

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1. Introduction

There is an increasing trend in manufacturing companies to prioritize environmental impact reduction due to growing international attention on global warming and stricter environmental regulations [1]. According to a report from the International Energy Agency (2015), the manufacturing industry contributes more than 35% of CO_2 emissions and consumes nearly one third of energy on a global scale [2]. Meanwhile, industrialization evolves towards the fourth generation (Industry 4.0) through digitalized and intelligent manufacturing, which aims to achieve higher levels of efficiency and productivity with less input and lower cost.

Industry 4.0 is supported by the advancement of information and communication technologies (ICT) and data storage [3]. In this sense, Industry 4.0 can be summarized as a collaborative network with eight key enabling technologies: Cyber Physical Systems (CPS), Internet of Things (IoT), cloud computing, big data analytics, Virtual Reality (VR)/Augmented Reality (AR), intelligent robotics, Industrial Artificial Intelligence (IAI), and Additive Manufacturing (AM) [3–6].

Since the expression "Industry 4.0" was first introduced at the Hanover Fair in 2011 in Germany [7], it has been a promising approach to improve overall operation performance by integrating manufacturing and business processes [3]. At the same time, Industry 4.0 can provide plentiful opportunities for environmental sustainability beyond economic benefits [4]. IoT enables real-time monitoring and obtains energy consumption data, thus optimizing and saving energy in manufacturing [8,9]. AM allows customized design and production, contributing to resource and waste reduction [10,11]. CPS enables a transparent production network with efficient communication, thus reducing emissions attributed to saved transportations [12,13].

However, a recent survey study by Brozzi et al. (2020) shows that companies seldom consider Industry 4.0 beneficial for environmental sustainability, and economic opportunities are prioritized over environmental and social gains [14]. Furthermore, there are also studies showing a negative impact of Industry 4.0 on the environment. The widely used and fast updated electrical and electronic equipment and devices from CPS and IoT produce a high amount of e-waste [15,16]. The production and use of ICT consume a growing amount of materials, which speeds up the depletion of natural resources [4]. The increasing demand of energy supply on digitalization and data centers generates abundant emissions [17]. Therefore, it is critical to account for both the potential positive and negative effects on the environmental sustainability of digitalization in manufacturing.

1.1. Environmental Sustainability in Manufacturing

Sustainability has been attracting increasing global attention. The most widely adopted definition of sustainability is from the Brundtland Report (1987): "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [18]. In the light of this definition, Glavic and Lukman (2007) reviewed sustainable development as a process that "emphasizes the evolution of human society from the responsible economic point of view, in accordance with environmental and natural processes". In this paradigm, the limitations of environmental resources "are considered in order to contribute to present and future generations' welfare" [19]. Similarly, Goodland (1995) defined environmental sustainability as "a set of constraints on the four major activities regulating the scale of the human economic subsystems: the use of renewable and nonrenewable resources on the source side, and pollution and waste assimilation on the sink side" [20]. Therefore, environmental sustainability can be defined as the development of "meeting the resource and services needs of current and future generations without compromising the health of the ecosystems that provide them" [18,21].

Manufacturing is the result of "humanity's rational desire for continuous development and growth" [22]. Environmental sustainability in manufacturing involves stabilizing the balance between manufacturing activities and their impact on the natural environment. The links between manufacturing operations and the natural environment are gradually becoming recognized [23], thus motivating manufacturers to prioritize environmental sustainability in their operation strategy. Meanwhile, the development of digitalization increases the competitive pressure within manufacturing companies, as the power of technology ensures higher quality, lower costs, and shorter delivery times. This raises the industrial standards and requires companies to go beyond the deployment of management philosophies based exclusively on efficiencies [24]. Therefore, manufacturing companies are increasingly taking environmental issues into their strategy development by promoting manufacturing processes that minimize environmental impact [25]. Thus, the concept of sustainable manufacturing was defined by the U.S. Department of Commerce as "the creation of manufactured products that use processes that minimize negative environmental impact, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound" [26].

To reach sustainable manufacturing, the environmental dimension cannot be isolated from economic and social sustainability [27]. Being economically sustainable involves the organizational vision, to create economic value either through increased added value or through cost reduction in production, with the purpose of assuring the possibility of delivering products and services to the market while having a profit between revenues and costs [27]. The social aspect relates to the organizational vision to generate value in order to perform fair business practices to benefit the employees, the community, and society [28].

When looking at sustainable manufacturing from a product perspective, O'Brien (1999) and Alayón et al. (2017) recommended the use of 3R: "Reduce, Reuse, and Recycle" to extend the lifecycle of products [29,30]. 3R aims to optimize production by utilizing reduced natural resources, producing minimum pollutions, emissions, and wastes [31]. Sarkis (2001) focused on the manufacturing process developments from the environmental perspective, and claimed that it could be linked to issues of Reduction, Reuse, Recycling, and Remanufacturing [32].

Furthermore, based on the 3R principles, Jawahir (2016) proposed a broader, innovation-based 6R methodology for products over multiple lifecycles: Reduce, Reuse, Recycle, Recover, Redesign, and Remanufacture [31]. This 6R approach sets the basis for sustainable manufacturing with "a closed-loop, multiple product lifecycle system" [31]. Moreover, the 6R methodology aims to retain the most possible resources within the loop, while producing minimal waste and emissions, without compromising manufacturing efficiency. Resources, waste, and emissions are the main environmental indicators used in manufacturing [25].

According to indicator categorization from the National Institute of Standards and Technology (NIST) [25], environmental indicators are categorized by the impact of emissions, resource consumption, pollutions, and the natural habitat conservation [25]. Life Cycle Assessment (LCA) has become the most common method for environmental impact evaluation in manufacturing [26]. As per ISO 14040 definition, LCA addresses the potential environmental impact over a product's lifecycle from raw material acquisition through production (cradle to gate), use, end-of-life recovery, and disposal [26]. It can be used for analyzing single products or services, or for comparing products or services that fulfill similar functions [33].

The product lifecycle adopted in this study is defined as Design (including material acquisition), Production, Transportation, Use, End of life, and Disposal [26]. The *Product* is defined as the output of the manufacturing process.

1.2. Digitalization and Industry 4.0 Related Technologies

Defining *digitalization* requires clarifying and relating to the concept of *digitization*. *Digitization* was defined as "the technical process of converting analog signals into a digital form, and ultimately into binary digits, and is the core idea brought forward by computer scientists since the inception of the first computers" based on work by Tilson (2010) and Hess (2016) [34]. In other words, *Digitization* implies the technical potential of separating information from physical data carriers and storage [34]. On the other hand, *digitalization* is described as "the manifold sociotechnical phenomena and processes of adopting and using these (digital) technologies in a broader individual, organizational, and societal context" [34]. This definition aligns with the statement of Yoo et al. (2010); digitalization consists of both social and technical dimensions [35].

The fourth industrial revolution is driven by real-time data exchange and flexible manufacturing [4], underpinned by the advancement of both ICT and data storage [3], thus enabling customized production. As mentioned earlier, Industry 4.0 can be understood through its fundamental components, the eight key enabling technologies. In other words, these *digital technologies* are the technologies indicated in [34] that enable the *digitalization* in the fourth industry revolution.

According to Lee et al. (2015), by integrating CPS with manufacturing, it would transform today's factories into an Industry 4.0 factory [36]. The 5C architecture of CPS, namely Connection, Conversion, Cyber, Cognition, and Configuration, is the 5-level CPS structure. Connection acquires reliable and accurate data from machines and equipment [36], which is the similar function IoT achieves. Conversion means data can be inferred to information [36]. Similarly, Intelligent Robotics is capable of inferring, perceiving, and learning based on the three levels of imperative, autonotic, and cognitive intelligence [37], and AM is recognized as a transformative technology [38]. The Cyber level acts as the central information hub in this architecture. Correspondingly, Big Data Analytics refers to techniques adopted to analyze and acquire intelligence from big data [39], and cloud computing is "a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources that can be rapidly provisioned and released with minimal management effort or service provider interaction" [40]. Cognition properly presents the acquired knowledge to expert users and supports the correct decision to be taken [36], which is similar to what VR and AR aim for as a decision support tool [9,41]. Configuration is the feedback level from cyber space to physical space and acts as "supervisory control to make machines self-configure and self-adaptive" [36], similar to what IAI aims for "to make the hidden problems in an industrial system explicit, then managing and avoiding them while they remain hidden" [42]. Figure 1 illustrates the applications and techniques associated with each level of the 5C architecture [36] and the corresponding eight digital technologies categories used in this study. Note that some technologies overlap with multiple layers; however, the categories are mapped with the layer that is the most relevant for the technology applications analyzed in this study. Table 1 further provides a description for each technology category using definitions from the literature.

Table 1. Definition of Industry 4.0 technologies as used in this paper.

5C Architecture	Definition of the Eight Technology Categories
Connection level	1. Internet of Things (IoT) It is a "global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies" [43]. IoT connects machines equipped with sensors and actuators to the internet, thus enabling the machines to generate, process, and communicate data in real-time, to either humans or machines [44].
Conversion level	2. Intelligent robotics/Cognitive robotics New generations of robots are evolving for greater utility and becoming more autonomous, flexible, and cooperative [45]. Wang (2010) defines it as an autonomous robot, capable of inferring, perceiving, and learning based on the three-levels of imperative, autonomic, and cognitive intelligence [37].
	3. Additive Manufacturing (AM) According to American Society for Testing and Materials (ASTM) 2792-12, ASTM has defined AM as "processes of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing fabrication methodologies" [46,47].
Cyber level	4. Big Data analytics It refers to techniques adopted to analyze and acquire intelligence from big data [39], which is defined as "high-volume, high-velocity, and/or high variety information assets that demand cost-effective, innovative forms of information processing for enhanced insight and decision making" [48]. Volume means the magnitude of data; velocity refers to the rate of data generated and the speed at which it should be analyzed and acted upon; variety refers to the structural heterogeneity in a dataset [39].
	5. Cloud computing It is a set of IT services provided over a network and allows machine data and functionalities to be deployed on the cloud [8]. According to NIST, cloud computing is "a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources that can be rapidly provisioned and released with minimal management effort or service provider interaction" [40].
Cognition level	6. Virtual Reality (VR)/Augmented Reality (AR) VR is an "advanced human–computer interface that simulates a realistic environment and allows participants to interact with it", which aims to establish a relationship between the participant and the created environment [41]. AR, on the other hand, turns the real environment into a digital interface by interacting with virtual objects in the real world [8].
Configuration level	7. Industrial Artificial Intelligence (IAI) It depends on the integration of computer science, AI, and domain knowledge, which is determined by the characteristics of fragmentation, individualization, and specialization of problems within the industry [42]. It firstly aims to make the hidden problems in an industrial system explicit, then managing and avoiding them while they remain hidden; its second objective is to "accumulate, inherit, and apply knowledge on a large scale" [42].
Relevant to all levels of the 5C architecture	8. Cyber Physical System (CPS) Defined as transformative technologies enabling seamlessly integrated systems in their physical assets and computational capabilities [36], providing and using data-accessing and data-processing services available on the internet [49]. A CPS involves intelligent connectivity, sophisticated data management and advanced computational capacities, which requires exponential growth in the ICT infrastructure [50].

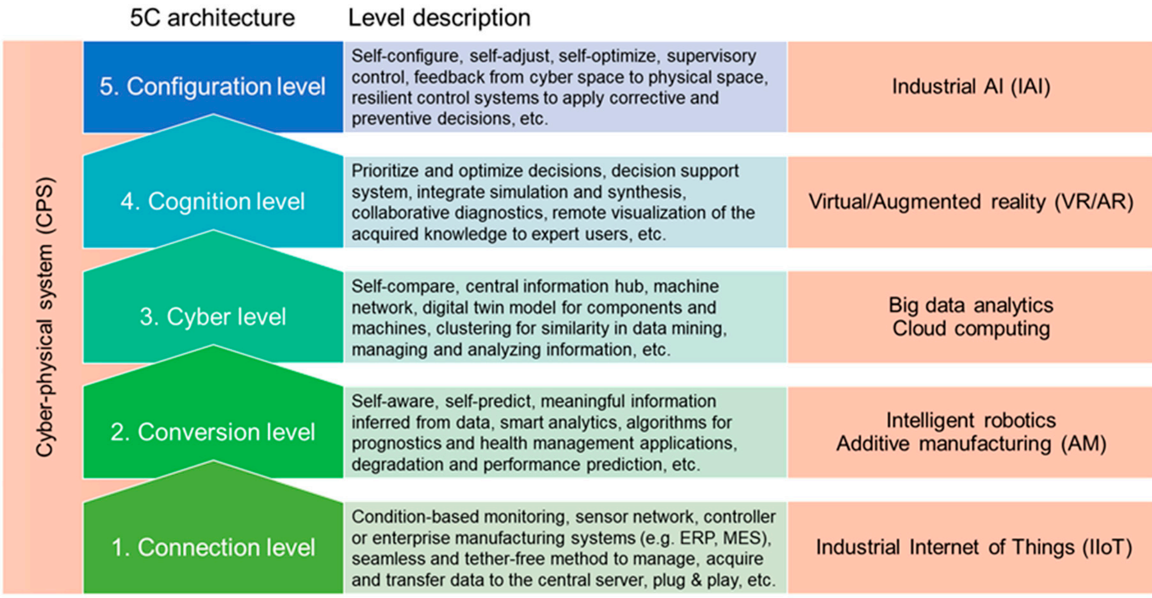

Figure 1. Applications and techniques associated with each level of the 5C architecture and technology categories used in this paper (orange boxes); adapted from [36].

1.3. Digitalization and Environmental Sustainability

Digitalization enables manufacturing processes to be in a fully integrated, automated, and optimized production flow, and brings benefits to manufacturing companies in terms of productivity, revenue growth, employment, and investment [45]. At the same time, the development towards digitalization provides opportunities for more environmentally sustainable manufacturing [51]. The discussion of environmental impact from digitalization has been a subject of systematic research for about 20 years [52]. The relationship between digitalization and environmental sustainability remains a difficult and uncertain research topic due to the pace of technological and societal change [52].

The environmental impact of digitalization is discussed both from positive and negative perspectives. Industry 4.0 could unlock the full potential of green manufacturing [3,53], through comprehensive digitization that provides more accurate, higher quality data, and real-time event management [6]. The impact of Industry 4.0 on environment develop a complex question [15]. Oláh (2020) investigated the impact of Industry 4.0 on organizations' operational scenarios, and the integration of Industry 4.0 attributes and Sustainable Development Goals (SDGs), thus providing advices on policies adoption for stakeholders and governments [6]. Another study from de Sousa Jabbour et al. (2018) argued that Industry 4.0 technologies have the potential to support environmental sustainability in manufacturing [4]. It proposed critical success factors that could unlock the full potential of Industry 4.0's integration and environmental sustainability, mainly applying to business management [4]. Zhang et al. (2019) assessed the benefits of adopting Industry 4.0 technologies with a case study comparing the environmental performance of manufacturing a household refrigerator in a smart factory with the one manufactured in a conventional factory [54].

Furthermore, Stock et al. (2016) claimed that the allocation of materials, energy, and water can be efficiently done based on the intelligent cross-linked value creation modules [51]. Statistically, as stated by the Association of German Engineers, digitalization may result in a 25% increase of resource efficiency [16]; it also affirms that digitalization has the potential to reduce carbon emissions by 20% [16]. CPS and IoT enable transparency in manufacturing through real-time process monitoring of resource consumption, thus providing production management a solid basis for improved responsiveness [6,12]. Intelligent robotics increases productivity and stabilizes quality in manufacturing, which leads to higher resource efficiency with less waste [55]. AM improves resource efficiency through just–in-time production closer to the end-user and reduces waste through customized production [11,56]. As proposed by Chang et al. (2017), VR or AR assisted platforms can be used for prototyping at the design stage, eliminating the resources and energy of producing physical prototypes [56]. Lee (2020) and Junior et al. (2018) stated enormous potential of environmental benefits brought by the "carefree operation" through a platform consisting of IAI, cloud computing, and big data, such as minimized breakdown, "just in time" spare part provision, and smart energy and resource distribution [42,57].

On the contrary, some scholars argue that the production and use of digital technologies consume more resources and energy, as well as produce more waste [6,15,58]. As a consequence, the rapid growth of digital technology exploitation, including the "rebound effects", speeds up the depletion of natural resources; for example, the number of transistors that can be packed into an integrated circuit doubles every 18 months [3]. Digitalized manufacturing is more energy intensive, generating increasing electricity demands to meet the energy demand of data centers and their supporting networks [17]. Moreover, waste from ICT devices and hardware has become one of the priority streams in waste management [59,60]. These challenges are not only consequences of growing quantities of waste, but also the complexity of the electrical and electronic waste, caused by the wide variety of highly integrated devices and systems from accelerating technological innovations [60].

1.4. Research Aim and Research Questions

This paper seeks to explore both positive and negative environmental impacts from digitalization by studying the existing literature, providing implementation practices for industrial practitioners to better harness digital technologies in an environmentally friendly manner. This exploratory study is a step forward towards the understanding of the environmental impact of digitalization in manufacturing. Given the lack of studies on the overall implications of digitalization on environmental sustainability in the context of Industry 4.0, this study proposes the following two questions:

RQ1: *What are the environmental impacts of digitalization in manufacturing?*
RQ2: *How can digitalization support to reduce environmental impacts in manufacturing?*

The use of *digitalization*, instead of *Industry 4.0*, intends to include a broader sense of digitalized technologies, since many manufacturing companies are in the transition towards digitalization, but are not necessarily described as adopting technologies associated with Industry 4.0. *Manufacturing*, instead of *Production*, covers a broader field of study, such as the design of product, manufacturing processes (or *production*), transportation, and customer service.

To address the research gap identified, this paper presents a review of the environmental impact of digital technologies and proposes a new perspective to consider the environmental sustainability of manufacturing systems in the Industry 4.0 era. Both positive and negative impacts are included to illustrate the overall implications of digitalization. The findings presented can support manufacturing companies select and use digital technologies in a more environmentally friendly way: understanding the resource demands of digital technologies at each stage of the product and technology lifecycles, being aware of the potential environmental impacts when investing in new technologies, and using digital technologies directly to reduce the environmental impact of manufacturing systems.

2. Methods

This study applied a qualitative research method. A literature review was conducted in July 2020 to identify and analyze the environmental implications of digitalization in manufacturing. The study aimed at collecting information available in academic literature focusing on the industrial engineering domain, then synthesizing the findings in a structured manner using a product lifecycle model. Based on the literature analysis, a new perspective was proposed to illustrate the findings and provide foundations for researchers and practitioners to make use of these findings. Therefore, the approaches adopted in this study were exploratory and theory building [61].

Literature review is defined by Hart (2018) as "the selection of available documents on the topic, which contain information, ideas, data and evidence written from a particular standpoint to fulfill certain aim" [62]. The ideas and work of others provide the researcher with a framework for their own work, making possible to understand the interrelationships between the subject being studied and other subject areas [62]. It generally includes procedures of searching, classifying, reading, analyzing, organizing, and expressing [62]. Instructed by Hart (2018) [62], the review consisted of three main steps: selection and evaluation of literature, content analysis, and results description, as illustrated in Figure 2.

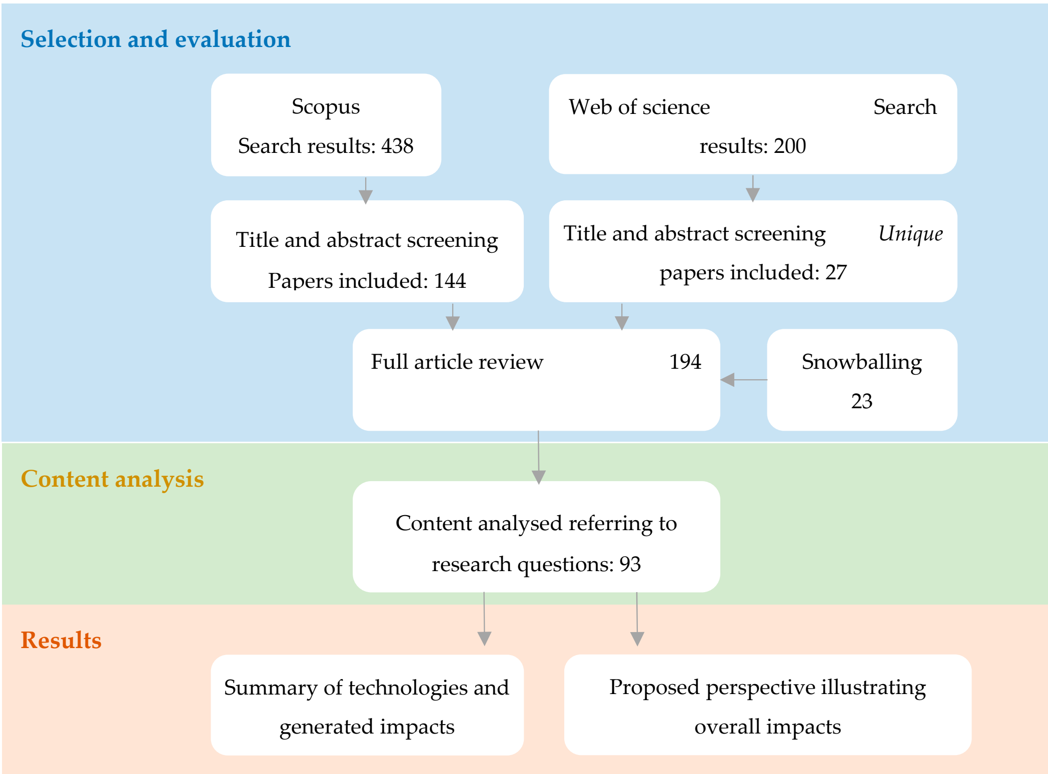

Figure 2. Literature review steps and search results based on published work up to July 2020.

2.1. Literature Search, Selection, and Evaluation

Three set of keywords were selected for the literature search: digitalization (set A), environmental impact (set B), and manufacturing (set C). All three sets included related terms, singular and plural forms, as shown in Table 2. The search query combined keywords with the "OR" operator within each set and the "AND" operator between sets. The operator "W/2" in set B narrowed down the results including the term "environment*" and eliminated its use in other contexts, such as "business environment" or "work environment". Scientific databases were used, with Scopus being the primary source and Web of Science the supplementary source.

Table 2. List of keywords in the literature search query.

Search Query: Set A *AND* Set B *AND* Set C		
Set A	**Set B**	**Set C**
(digital * *AND* technology) *OR* digiti * *OR* digitali * *OR* (cyber *AND* physical *AND* system) *OR* industry * 4.0	(environment * *W/2* sustainab *) *OR* (environment * *W/2* impact)	manufactur * *OR* production

* is the truncation symbol that used to capture all relevant articles by searching for words with the same root.

The title and abstract screening filtered the articles under the main topic of digital technologies and environmental sustainability in manufacturing. After 144 articles were selected out of the initial 438 search results on Scopus, the same search query was applied in Web of Science. With an initial number of 776 articles, the first 200 articles sequenced by citation rate were filtered with title and abstract review. This step was carried out for two purposes: to check the duplication rate in the findings from Scopus, and to check if any influential publications were missing (i.e., highly cited). Most of the findings from Web of Science overlapped with Scopus, which confirmed the coverage of highly relevant articles with the primary search.

Through snowballing, 23 articles were added, because they were found relevant in the reference list. In total, 197 articles were reviewed to further exclude irrelevant ones that did not approach to answer the research question. The search results, filtering steps (including inclusion and exclusion criteria), and selected articles were documented; Endnote was used to store the bibliographical information and group the final sample of 93 articles.

2.2. Content Analysis

A spreadsheet was created to disseminate the selected 93 articles. The analysis was based on the following criteria: (i) the focused digital technologies, (ii) the manufacturing stage that digital technologies are implemented (application), (iii) the environmental impacts resulted from the implementation of the digital technologies, (iv) whether the generated environmental impact is positive or negative, and (v) whether the other two sustainability pillars are also discussed.

The first four criteria were derived from the research questions: "What are the environmental impacts of digitalization in manufacturing?" and "How can digitalization support to reduce environmental impacts in manufacturing?". Criteria (v) was added during the analysis process. It was noticed that the articles also discussed the other two sustainability perspectives, although only *environmental* perspective was used in the search query. To identify the level of focus on economic and social aspects, the authors provide a classification based on the appearance of certain terms in the text of each article. For instance, the terms *economy*, *economics*, *cost*, and *profit* were selected as indicators of focus on economic aspect. The terms used to identify the focus on social sustainability were *social*, *society*, *human*, *people*, *citizen*, *user*, *employee*, *worker*, *security*, and *safety*. The findings were categorized according to the number of times the selected terms appear on each text, as high (over 50), medium (over 25, less than 50), and low (over 10, less than 25) level of focus. These levels were used to describe how much the analyzed articles related to economic and social aspects.

From the literature analysis, it was observed that not all the environmental impacts described in literature are from implementation of digital technologies in manufacturing; the manufacturing of digital technologies (hardware) also generates its own environmental impact. Therefore, hardware manufacturing was included into criteria (iii).

2.3. Synthesis and Results Description

Based on the content analysis, it was gradually observed that the environmental impacts come from two lifecycles: the product lifecycle for products manufactured with support from digital technologies and the lifecycle of the digital technology itself (hardware). This perspective was also summarized to illustrate the overall relationship between digitalization in manufacturing and the generated environmental impact.

The results description was illustrated with an Entity Relationship Model (ERM), which adopts a natural view reflecting that the real world consists of entities and relationships [63]. It contains relevant information concerning entities and relationships that the enterprise is mostly interested in [63]. Hence, the ERM captured and described the relationships within the scope of this study, i.e., relevant to the research questions. Other aspects, e.g., data-driven services outside manufacturing or customer-centric data analytics without direct links to manufacturing, were not included.

2.4. Research Quality and Methodological Limitation

According to Kalsson (2016), construct validity means that "the operational measures used to measure the constructs actually measure the concepts they are intended to measure" [61]. This implies that the researcher collects the intended information. In this study, this is supported by the fact that the search query was defined according to the terms used in the research questions and using specific combinations of keywords to obtain relevant publications; such as "Digitalization", "Environmental sustainability", and "Manufacturing".

Reliability is about consistency, replicability, and robustness of the methods employed for data collection and data analysis [61]. This was supported by the stated procedures in this section. Although objectivity is highly desired, the qualitative analysis was influenced to some extent by the authors' preconceived notions of sustainable manufacturing (researcher bias); thus, a degree of subjectivity is acknowledged in the results presented. However, prior knowledge about sustainability (expertise) was necessary to interpret the findings and propose a new perspective for the adoption of digital technologies towards more sustainable manufacturing.

3. Results

In this section, the results from the literature review contribute to expanding the scientific knowledge on the implications of digitalization on environmental sustainability. This takes shape in the following findings: (i) a synthesis of the overall environmental impacts of digitalization, including both positive and negative impacts; and (ii) a new perspective to support environmental sustainability through the application of digitalization in manufacturing.

3.1. Preliminary Analysis

3.1.1. Yearwise Publication Trend

The selected articles were published from 2004 until July 2020, which corresponds to the time when environmental sustainability became the object of study of systematic research [15]. The number of studies increased rapidly from 2016 and continues to do so: in the first six months of 2020, the number of publications was already similar to the previous year and 10–20 times more than five years earlier. This indicates a rapidly growing trend in research linking digital technologies and their environmental sustainability, reflecting the growing importance and urgency of addressing environmental issues (see Figure 3).

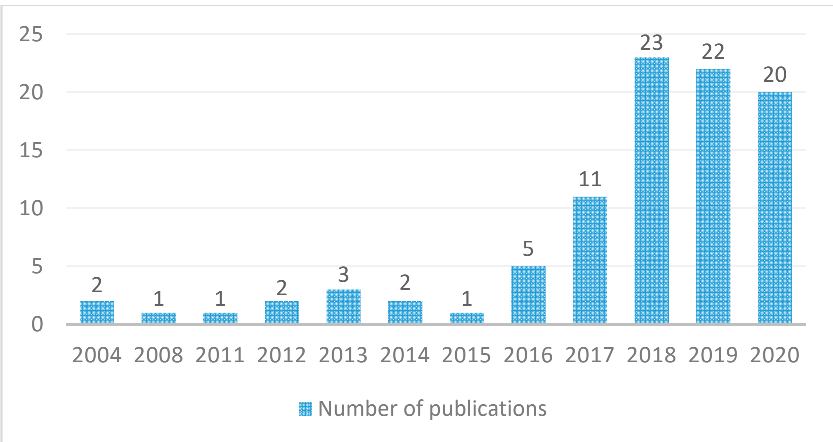

Figure 3. Number of studies per year from the analyzed publications.

3.1.2. Contribution from Journals

There are ten publications from the journal Sustainability, and nine from Journal of Cleaner Production, which are the two largest contributors. It is then followed by the journal Resources, Conservation, and Recycling, which has three publications. The journals International Journal of Advanced Manufacturing Technology and Journal of Manufacturing Technology Management and Social Sciences have two publications each.

3.1.3. Contribution from Authors by Country

The authors' affiliations from different countries were ranked, showing that Germany (12 papers), England (11 papers), and the USA (10 papers) dominate the list, with 33 papers out of the selected 93 papers. The list is followed by Italy and Spain, with contributions of eight and seven papers, respectively. Brazil and China are the next in the list, with five papers each. The list in Figure 4 shows that the majority of contributions are from authors in Europe and the USA. Nevertheless, authors in Asia also contribute, with 15 papers out of the selected 93 papers.

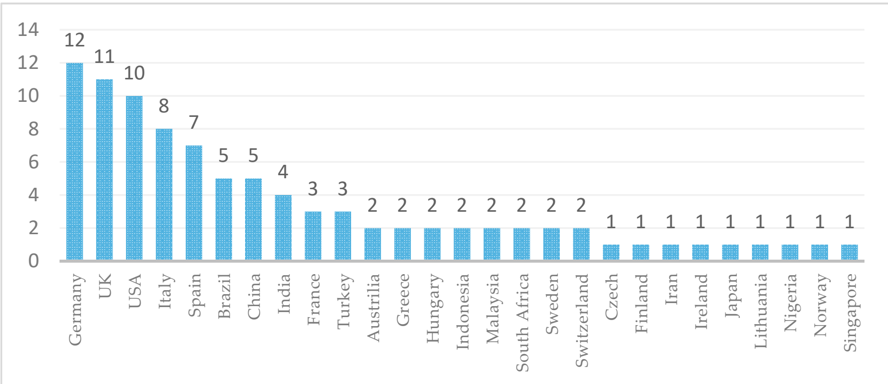

Figure 4. Country wise publication details.

3.1.4. Keywords Statistics

The most frequently used keywords from the selected papers were "sustainable development" (34%), "environmental impact" (32%), and "Industry 4.0" (31%). It was then followed by "manufacture" (23%) and "sustainability" (23%). Other keywords used include "environmental sustainability" (15%), "life cycle" (15%), "embedded system" (13%), "manufacturing" (12%), and "cyber physical system" (11%). It shows that the keywords used in the selected papers match the research topic of this study (see Figure 5).

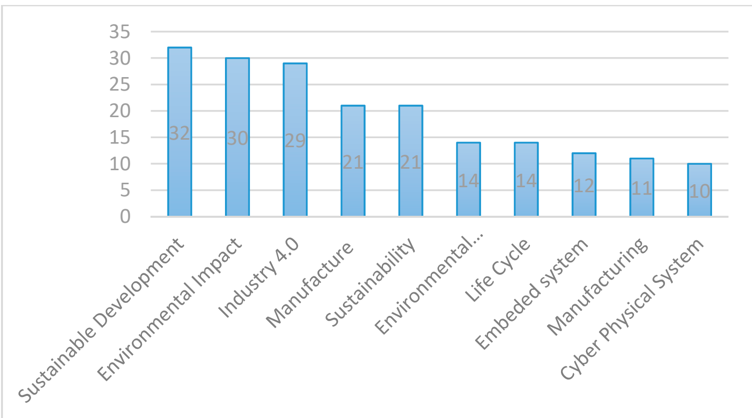

Figure 5. Keywords distribution.

3.1.5. Mapping of Literature Analysis

To answer the research questions, the analyzed literature was categorized according to (i) the type of digital technologies, (ii) the studied lifecycle (product lifecycle or technology lifecycle), (iii) the positive and/or negative environmental impact, and (iv) interconnection with the other two sustainability pillars. Firstly, (i) shows the technology focus from each analyzed paper, which could be one or more of the eight digital technologies. As shown in Table 3, the articles categorized as "Industry 4.0" indicate that the technology was discussed in a general level, instead of any specific one(s). Secondly, (ii) illustrates that the focus is the manufactured product lifecycle and/or the digital technologies' hardware lifecycle. Thirdly, the positive and/or negative impact from (iii) is presented with color variants: green represents positive impact on the environment, while red represents the negative impact. The circle with both red and green means both positive and negative perspectives were discussed in the paper. Finally, in category (iv), an analysis of the sustainability focus on economic and social perspectives besides the environmental dimension was carried out; plus signs are used to represent the major (+++), medium (++) and low (+) level of focus.

Table 3. Mapping of literature analysis.

No.	Paper	Digital Technology	Lifecycle	Positive/Negative Environ. Impact	Other Two Pillars	
					Economic	Social
1	[24]	Industry 4.0	P	🟢	+++	+++
2	[6]	Industry 4.0	P, T	🔴🟢	++	+
3	[55]	Industry 4.0	P	🟢	+++	++
4	[64]	Industry 4.0	P	🟢	+++	+
5	[14]	Industry 4.0	P	🟢	+++	+++
6	[65]	Industry 4.0	P	🟢	+++	+++
7	[66]	AM	T	🔴	+	
8	[67]	IoT	P	🟢	+++	
9	[58]	CPS	P, T	🔴🟢	+++	
10	[68]	Big Data	P	🟢	++	+
11	[69]	Industry 4.0	P	🟢	+++	
12	[70]	Cloud	P	🟢	++	++
13	[71]	Big Data	P	🟢	++	
14	[72]	CPS	P	🟢	+++	+++
15	[73]	CPS	P	🟢	++	++
16	[74]	Big Data	T	🔴	++	++
17	[75]	Cloud, CPS, IoT	P	🟢	+++	++
18	[76]	Big Data	P	🟢	++	
19	[77]	IAI, Big Data	P	🟢	++	+
20	[78]	CPS	P	🟢	+++	++

Table 3. *Cont.*

No.	Paper	Digital Technology	Lifecycle	Positive/Negative Environ. Impact	Other Two Pillars	
					Economic	Social
21	[79]	CPS, VR, AR, IoT	P		++	++
22	[80]	CPS	P		++	
23	[81]	CPS	P		++	
24	[82]	AM	T			
25	[83]	Industry 4.0	P		++	+
26	[17]	Big Data	T		+	
27	[84]	Industry 4.0	P		+	+
28	[85]	AM	T		++	
29	[86]	Industry 4.0	P		++	++
30	[87]	Industry 4.0	P		++	+++
31	[7]	Industry 4.0	P		+	+
32	[88]	CPS	T		+	
33	[54]	Industry 4.0	P		+	
34	[16]	CPS	P, T		++	
35	[89]	IoT	P		+	+
36	[53]	Big Data	P		+++	
37	[90]	CPS	P		++	++
38	[91]	CPS	P		++	++
39	[92]	CPS	P		+++	
40	[93]	Robotics	P		+	+++
41	[94]	IoT	P		+++	++
42	[3]	CPS, AM	P		++	+
43	[95]	Big Data	T		++	++
44	[96]	Industry 4.0	P		+++	+++
45	[97]	Industry 4.0	P		++	
46	[57]	Industry 4.0	P			+++
47	[98]	Industry 4.0	P			++
48	[99]	Industry 4.0	P		++	+
49	[100]	Industry 4.0	P		++	+
50	[5]	IAI	P		++	

Table 3. *Cont.*

No.	Paper	Digital Technology	Lifecycle	Positive/Negative Environ. Impact	Other Two Pillars	
					Economic	Social
51	[101]	Industry 4.0	P	●	+	++
52	[102]	CPS	P	●	++	
53	[50]	Industry 4.0	T	◐		+
54	[103]	IoT, Big Data	P	●	+++	
55	[104]	CPS	P	●	++	+++
56	[105]	Industry 4.0	P	●	+++	+++
57	[13]	CPS	P	●	+	
58	[106]	Industry 4.0	P	●	++	
59	[107]	Big Data	P	●	+	
60	[108]	CPS	T	◐	+	+
61	[109]	Industry 4.0	P	●	+++	++
62	[110]	Block Chain	P	●	++	+
63	[111]	Industry 4.0	P	●	++	++
64	[112]	Industry 4.0	P	●	+	++
65	[4]	Industry 4.0	P	●	+	++
66	[27]	IoT	P	●	++	++
67	[113]	CPS	P, T	◐	++	++
68	[114]	CPS	P	●	++	+
69	[115]	CPS	P, T	◐	+	
70	[116]	Industry 4.0	P	●	++	
71	[117]	Industry 4.0	P	●	+	+
72	[118]	IoT	P	●	+	
73	[9]	Industry 4.0	P	●	+	
74	[119]	Industry 4.0	P	●	++	+
75	[8]	Industry 4.0	P	●	+	
76	[12]	CPS	P	●	+++	+
77	[11]	AM	P, T	◐	+++	++
78	[51]	Industry 4.0	P	●	++	+
79	[120]	CPS	P	●	++	+

Table 3. *Cont.*

No.	Paper	Digital Technology	Lifecycle	Positive/Negative Environ. Impact	Other Two Pillars	
					Economic	Social
80	[121]	AM	P		++	++
81	[122]	AM	P		++	
82	[22]	AM	P, T		+	++
83	[33]	ICT	T		+	++
84	[123]	CPS	P		+	++
85	[26]	ICT	P		++	++
86	[124]	ICT	P		+	
87	[125]	ICT	P		++	+
88	[126]	ICT	P, T		+	++
89	[127]	ICT	P		++	++
90	[59]	ICT	P, T		++	++
91	[60]	ICT	T		++	+
92	[128]	ICT	T			
93	[15]	ICT	T		++	+

The most commonly studied technologies were Industry 4.0 and CPS. Papers that introduced various impacts from different technologies were also categorized into Industry 4.0. The detailed impact from each technology will be further explained in Section 3.2. From Table 3, the product lifecycle dominates the discussion focus and mainly relates to the positive impact on the environment. On the contrary, the technology's lifecycle is rarely the focus and usually generates negative impact on the environment. Furthermore, the focus on economic and social sustainability in addition to the environmental aspect appears to be highly relevant, with 88 papers (accounting for 95%) on the economic sustainability pillar and 62 papers (accounts for 67%) on the social pillar. There are 20 out of the selected 93 papers locating the economic pillar as the highest claimed focus, in addition to the environmental focus, and 10 out of 93 locate the social perspective as the highest focus.

3.2. *Digitalization in Manufacturing and Impacts on the Product Lifecycle*

Based on the studied literature, digitalization in manufacturing has both positive and negative impacts on the environment. We distinguish between impacts occurring in two lifecycles: the manufactured *product lifecycle* (presented in this section) and the digital *technology lifecycle* (presented in Section 3.3). Table 4 summarizes the environmental impact from the *product lifecycle*.

3.2.1. Positive Impacts

In the manufactured product lifecycle, the environmental impact of digitalization is mainly positive throughout the value creation process: Design, Manufacturing Processes (Production), Transportation, Use, and End-of-Life recovery. In the following, the impact from each level of the 5C will be explained along with the product lifecycle.

Table 4. Environmental impact of digitalization in manufactured product lifecycle.

5C	Technology	Design	Production	Transportation	Use	End of Life
Configuration level	IAI		**EN**: Smarter scheduling [5,111]		**EM**: Instant support [112]	
Cognition level	VR/AR	**M, EN**: Replacing physical product [112]			**EN**: Working virtually [17] **EN**: Server virtualization [17]	
Cyber level	Big data	**EN**: Layout design [107]	**M, EN**: Optimization of consumption [111] **EN**: Preventive maintenance [111] **EN**: Condition monitoring [8,53,95] **M, WS**: Reuse waste [6,76] **M**: Data driven decision support [102] **WA, EM, HA**: Predictability and control [57]	**EM**: Autonomous distribution [65] **EN**: Data support optimization [79]		
	Cloud computing		**WA, EM, HA**: Predictability and control [57]			
Conversion level	Intelligent Robotics		**M, EN, WS**: Damage reduction, better quality [107] **M, EN**: Higher efficiency [55,107] *EN*: High consumption [55]			
	AM	**M, EN, WS**: Prototyping [11,22,24,102]	**WS, M**, *EN*: Manufacturing of tool and product [6,102,122] **EN**: Reduced by optimized design [55,122] **WS**: Using waste as raw material [3] **M, EN**: Optimized quality [11] *EN*: Heating required [11,85]	**EM, WS**: Onsite production [6,11,24,85,96,111,112]	**M, EN, EM**: Customization [55,111]	**M**: Optimizes quality in remanufacturing [11,79] **M**: Improved efficiency in reuse, repair, recycling; reduce waste. [11,24]
Connection level	ICT/IoT	**M, EM, W, EN**: Customized outsource/design; Efficient/transparent communication [24,27,54,96] *EM*: Frequent transportation [54]	**M, EN, WS**: Improvement of parameter setting [8,24,27,54,96] **EN, EM**: Higher efficiency [15,27,54] **M, EN**: Availability of reliable data [65,105,111] **EN**: Condition monitoring and control [6,9,53,65,80] **WS**: Tracking of weight and reason [89] **HA**: Proactive reduction [57]	*EN, EM*: Frequent delivery [54] **EM, EN**: Reduced within plant transport [54] **EM, EN**: Autonomous distribution [27,103,118] **M, EM**: Efficient communication [27,96]	**EN**: Condition monitoring [8]	**M**: Disassembly to order [67] **WS**: Monitoring of waste generated in remanufacturing [79].
CPS		**EN**: Optimized fuel consumption [8] **EN**: Flexible design configuration [102]	**M, EN**: Availability of reliable data [13,51,55,111] **M**: Reduced production [12] **EN**: Optimized material handling [106] **EN**: LCA data collection [115] **EN**: Smart scheduling [73,113]	**EN**: Reduced material delivery [12]	**EN**: Condition monitoring [8] **EN**: Remote support [8]	**M**: Monitors, controls, and optimizes [71]

EM: Emission. EN: Energy. H: Hazardous waste. M: Material. WA: Waste. WT: Wastewater. WT-E: Water emission. Abbreviations in bold signify a positive environmental impact; abbreviations in italics signify a negative environmental impact.

CPS and Connection level (IIOT):

At the *design* stage, IoT enabled manufacturing systems to enhance communication with suppliers by involving them in the design process, achieving an eco-design and a green supply chain. The case study from [54] changed the design of a refrigerator from the traditional bill of material-based into a module-based, which decreased the consumption of raw material and increased the level of standardization [54]. At the same time, this modular design reduced resetting time attributes through a simplified design, which reduced energy consumption [54].

In addition, the IoT platform also enables the possibility of integrating customers in the design stage, promoting resource and energy saving by customizing design in both product and delivery [27]. In that sense, the manufacturing resources and capacity can be scheduled with higher flexibility [27].

Furthermore, IoT platforms enable information transparency throughout the product lifecycle. The design performance can be improved through data interconnection from the later stages of product lifecycle [96]. Information from manufacturing, use, and even recycling stages can provide opportunities for design improvement [96]. The intelligent programming integrated in this IoT platform could carry out eco-design by incorporating an efficient management of energy consumption in product design [24]. Meanwhile, the amount of material consumption can also be optimized through information transparency enabled by intelligent programming [24].

Similarly, it is claimed by Ang et al. (2017), with a case study of a ship, that the gaps between the real and virtual world can be minimized with CPPS (Cyber Physical Production System), which can be used to connect manufacturing with design [8]. By mirroring the physical world to a virtual model, the automated "test-and-optimize" smarter ship design reduced the fuel and energy consumption [8]. It also estimates a completely automated design that will be capable of fully connecting to manufacturing and operation systems and predict market trends according to customer feedback [8]. With the current trend of digitalization development, this fully automated design is possible to execute in the next five to ten years [8]. Furthermore, the CPS implemented in [102] enables flexible design configuration of the energy supply components, thus leading to an optimized facility design for efficient energy supply [102].

In the *production* stage, the interconnection of processes allows machines to communicate through the network and share information about parameter setting, stock levels, problems or errors, and changes of demand [8,15,24]. From the point of material acquisition, modular design promotes conservation of raw material in production and reduces material consumption [54]. From the quality perspective, as illustrated in [8], defects found after the delivery of vessel could be monitored and fed back to the production process for improvement [8]. Moreover, the critical process parameters can be dynamically adjusted to assure quality [96]. In addition to raw material reduction and quality improvement, optimized parameters also lead to higher efficiency of material and energy consumption with increased equipment efficiency [27].

The incorporation of different sensors provides reliable data from manufacturing processes, which offers numerous opportunities for manufacturers to take proactive environmental activities [57,111]. Data regarding material and energy consumption, as well as waste generation, can be monitored and collected as a basis for decision making [51,55]. Accordingly, manufacturers can set environmental sustainability strategies based on the collected data [111] and provide feedback within the value chain to enable continuous improvement [105]. Junior et al. (2018) proposed that using sensors to monitor physical and environmental conditions would allow manufacturers to proactively and effectively reduce equipment and environment-related hazards [57].

Real-time data monitoring tracks the consumption of resources (like energy and water) and waste generation, and then responds to production management [6,9,65], enabling green manufacturing. Santos et al. (2019) show a dramatic reduction in the energy bill of €500 per year reached by the "plug&glean" implementation to track energy consumption [53]. Similarly, Bonfá et al. achieve a 10% energy saving by monitoring and adjusting the supply of compressed air, based on air pressure and variation of temperature demand [80]. Furthermore, the case study in [13] demonstrates a 20%

reduction by tracking and identifying improvement potential [13]. With a similar approach, [106] implemented status tracking on equipment to improve the Overall Equipment Efficiency (OEE), leading to an energy decrease by optimizing material handling [106].

IoT and CPS enable manufacturing companies to schedule production with higher flexibility [73,113]. The case illustrated by [113] shows a possible reduction of up to 60% of energy consumption by suggesting manufacturing companies plan their production according to the power plants' natural overproduction of energy through wind or solar energy [113]. Additionally, [73] argues that the CPS-based integrated energy management can reduce industrial energy use by 63%, contributing to the reduction of CO_2 emissions [73].

In addition to decreasing energy usage, IoT and CPS support the reduction of material consumption by tracking the components and Work in Process (WIP) [12,89,102]. Song et al. (2017) presented the main benefits of implementing CPS, which include reducing WIP and decreasing process time with a deployed monitoring system [12]. The case of [89] shows a successful implementation of IoT in a food manufacturing company while tracking waste generation [89]. With the support of big data analytics, the origin and reasons of the waste were tracked, recorded, and analyzed, contributing to an impressive 60.7% reduction of waste [89].

CPS can also be applied to assess environmental impact when integrated to LCA [115]. The implementation of CPS systems integrating LCA features introduces a quantitative basis to improve environmental performance [115]. The result shows a positive impact on environment by minimizing energy consumption and verifying the potential to achieve increased eco-efficiency [115].

During *transportation*, the CPS and IoT enabled platform promotes environmental sustainability by enhancing communication with customers [27,96], leading to a reduction of mistaken deliveries and waiting time. Communication with suppliers encourages heterogeneous resource transportation, which reduces transportation frequencies and distance [12]. Additionally, this platform promotes autonomous vehicles, enabling optimized routes with transportation reduction [27,103,118]. As illustrated by [103], the level of CO_2 emissions can be decreased by approximately 22%, attributed to the information transparency and big data analytics [103]. Moreover, smart production enabled by CPS and IoT platforms could reduce transportation distances within a manufacturing plant by 43%, mainly attributed to outsourcing the module design to the supplier [73].

At the *use* stage, the IoT and CPS enabled platform monitors and collects data, then gives feedback to the design and manufacturing processes for further improvement [8]. This platform also promotes remote support for customers by CPS-based remote control, which reduces time and transportation of onsite support [8].

At the *end–of-life* stage of a product, digitalization contributes to environmental sustainability mainly by extending the lifespan [67,79]. [67] proposes an approach to enable a disassembly-to-order system with the support of an IoT platform [67]. This system coordinates collection, disassembly, inspection and sorting, remanufacturing, reuse, and/or recycling operations in a reverse supply chain, leading towards closed-loop manufacturing and promoting multiple lifecycles [67]. Moreover, information flows throughout the product lifecycle support the development of design-for-disassembly [79].

Conversion level (AM and Intelligent robotics):

At the *design* stage, rapid prototyping in direct manufacturing is increasingly adopting AM technology [11,22,24]. It eliminates resource consumption of tools and customizes production [11,22], at the same time reducing the time to market with high customization [24]. The highly customized components/products production leads to less inventory of raw material and final products, thus contributing to a reduction of environmental impact [22].

The use of AM during *production* could support the reduction of material and energy use, leading to an optimized design with reduced waste generation [6,11,122]. Furthermore, AM does not require tooling, lubrication/cutting fluid, and casting release compounds, which would reduce environmental impacts [3,111]. The precise amount of material acquisition in AM reduces not only material and energy, but also scraps, leading to a further reduction of resource consumption [11,122]. Moreover, Ford and Despeisse (2016) highlight the possibility of reclaiming and reusing waste plastic filaments, misprints, and undesired outputs, enabling closed-loop manufacturing [11].

A number of studies claim that the reduction of *transportation* when using AM can significantly reduce transportations' carbon footprint [24,85,96]. This reduced transportation is mainly caused by the acquisition of precise quantities of raw material, and decentralized production geographically to consumers, thus reducing or even eliminating inventory [11,85,111].

In the use *stage*, compared with the traditional manufacturing, the on-demand high customization enabled by AM increases the chance of repairing or refurbishing products, contributing to resource and waste reduction [55,111]. At the *end-of-life* stage, AM can be applied in the remanufacturing processes to assure quality [11,71] and can reduce waste generation during the repair process [11,24].

Cyber level (big data analytics and cloud computing):

Big data analytics supports product *design* in decision making with various options and databased evaluation. The case provided by [107] demonstrates how big data offers options in layout design by analyzing data of different manufacturing scenarios [107]. As a consensus of balancing ten layout options, they proposed a final option, chosen for being effective and efficient in saving material handling costs and energy consumption [107].

During *production*, big data analytics based CPS and IoT platforms can support the reduction of environmental impact [8,53,111]. [111] indicates that preventive and predictive maintenance enabled by big data analytics extends the lifespan of equipment, reducing waste; it also shows that big data can reduce energy consumption through intelligent optimization [6,111]. Similar applications can also be used in ship manufacturing to optimize equipment usage and power consumption, leading to a 29% reduction of factory power consumption [8]. With the aid of big data analytics, manufacturing is able to produce to meet precise requirements, with better quality control, leading to an obvious reduction of resource consumption and waste generation [6]. Root cause tracking could also be done with big data, avoiding failures and wastes in future systems [76].

Cloud computing is usually applied in conjunction with other digitalized technologies; combined with big data analytics to improve data gathering, it can better predict and control water quality, air pollution, and contamination by hazardous waste [57].

At the *use* stage, big data enables automatically planning the optimum route during ship operations, which sets the fuel consumption to a minimum level [8].

Cognition level (VR/AR):

VR supports product *design* virtually with a digital twin and therefore reduces the cost and resources of producing physical prototypes [112]. This cost-effective simulation, control, and prediction enabled by VR can also reduce material and energy consumption by minimizing design error [112].

At the *use* stage, VR supports environmental sustainability by reducing physical devices. As illustrated by [17], the server virtualization technology reduces 13 servers and one storage in the case study, thus significantly cutting down energy efficiency per user by 90% and hidden environmental cost from e-waste by 98% [17].

Regarding the *end-of-life* stage, VR and AR could be used at the design stage, to support design-for-disassembly [71]. The integration of advanced technologies can elevate the possibility of turning end-of-life products back to in-life products through remanufacturing [71,79].

Configuration level (IAI):

During *production*, the application of IAI optimizes resource allocation, including material, energy, and water use, facilitating an integration with environmentally sustainable manufacturing [111]. IAI enabled intelligent robotics to increase energy efficiency [55] and quality performance [105]. As stated by Braccini and Margherita (2018), autonomous robots increase the precision of manufacturing processes, leading to a significant reduction of defect rates from 30% to 9% [105].

The practices listed above show the significant importance of digitalization applications in promoting environmental sustainability. Nevertheless, digitalization also generates a negative impact on the environment through the product lifecycle. The following section will explain these negative impacts.

3.2.2. Negative Impacts

Customized design provides certain benefits. However, it does increase transportation that involves suppliers and customers [54]. For the procurement, more frequent transportation is required for smaller batches and personalized modules; for the delivery to customers, more deliveries are needed to realize "just-in-time" [54].

AM shows great opportunities through highly customized design; however, it also adds a burden on the environment according to several studies [11,85,111]. It is claimed that AM is not energy efficient due to the heating required in manufacturing processes [6,11,111]. [85] brings up that the failure of the print, which is very common in AM, could increase material and energy consumption [85].

For the reasons already presented in this paper, it can be concluded that the environmental impact of digitalization in the product lifecycle is mainly positive. The negative impact on the environment is relatively small in the product lifecycle, especially compared with the positive impact. This is because most of the research only considers the environmental impact from the product lifecycle perspective. As stated in a few studies, the manufacturing and use of digital equipment and devices requires abundant resources and generates enormous wastes [4,15,16]. Therefore, the impact from the technology lifecycle should be included, when we stand from the ecological perspective. The next section will present the environmental impact from the technology hardware's lifecycle.

3.3. Digitalization in Manufacturing and Impacts on the Technology Lifecycle

The environmental impact of the technology lifecycle is entirely negative and mainly from the Production, Use, and End-of-life, as Table 5 shows.

Table 5. Environmental impact of digital technologies in technology lifecycle.

	Design	Production	Transportation	Use	End of Life
Technology lifecycle		*EM, M, EN*: ICT manufacturing [15,33,111] *WT, WT-E*: ICT manufacturing [60] *EM*: Life cycle of big data related devices, such as data center, ICT devices [74,95] *EM*: Components [13] *M, EN*: AM manufacturing [22,82] *HA*: AM manufacturing [22] *WA*: Freshwater for material production [82]		*EN*: ICT use [15,33,111] *EN*: Use of CPS [81] *EM*: Use of data center [74,95]	*EN*: ICT disposal transport [111] *WS*: ICT disposal [15,59,60,111] *EM*: Life cycle of big data related devices, such as data center, ICT devices [74,95]

EM: Emission. EN: Energy. H: Hazardous waste. M: Material. WA: Waste. WT: Wastewater. WT-E: Water emission. Abbreviations in bold signify a positive environmental impact; abbreviations in italics signify a negative environmental impact.

Production: Industry 4.0 technologies are equipped with ICT, e.g., RFID, micro-chips, semiconductors, displays, sensors, and micro-energy/harvesting, which cause a variety of undesirable environmental impacts [15,59,129]. The huge demand of ICT requires a massive amount of material. The usage forecast of sensors, for example, will increase from 4.4 billion (2015) to 11.2 billion by 2021, with a large variety up to 47 types that are mainly used in Industry 4.0 [129]. The production of semiconductors, from another point of view, causes substantial air emissions (acid fumes, volatile organic compounds, and doping gases), water emissions (solvents, cleaning solutions, acids, and metals) and wastes (silicon and solvents) [15]. Furthermore, the manufacture of ICT is energy intensive and demands large amounts of water in cooling and rinsing [15]; the energy use increases rapidly with higher purity [59]. At the component level, LCA shows that at least 1.2 kg of fossil fuel is needed to manufacture a 2-g dynamic random access memory chip, which is 300–600 times more than other manufactured goods [59].

Use: The major impacts from the use of ICT are energy consumption and/or CO_2 emissions [15,129]. The primary energy consumption is mostly applied in ICTs for CPS with cloud technologies and data center to process big data [59,129]. The energy use by RFID chips or sensors, which are frequently used for condition monitoring, are relatively low [129]. According to EPA (2017), the carbon emissions associated with data storage are approximately 35 kg of CO_2 per TB per year [95]. In addition to storage, transmitting data also consumes energy [95]. For example, a videoconference transmission between Switzerland and Japan in 2009 accounted for 200 Kwh per TB, significantly higher than the 46.33 kWh per TB estimated for storage [95].

End of life: Currently, only a very small proportion of ICT hardware is recycled [15,59,129]. RFID, consisting of raw material of aluminum, copper, and silver, has no significant recycling systems, since there are no economic incentives for recycling used RFID tags [129]. Similarly, there is no systematic recycling for displays and sensors, either due to a lack of economic efficiency or technical feasibility [129]. Therefore, the end-of-life ICT may contain hazardous metals, such as lead and cadmium [59]. Without proper recycling, a great amount of ICT goes to landfills or incineration [59], which generates abundant wastes, risk of exposure to hazardous materials, and harmful emissions from incineration [59].

To conclude, the environmental impact from the technology lifecycle is primarily negative, as summarized in Table 5. The environmental impact of manufacture, use, and disposal of technologies associated with Industry 4.0 has become a serious issue. We have to include the impact of technology cycle when we invest in new digital technologies.

4. Discussion

Industry 4.0 technologies have the potential to improve the operational performance of production. However, these technologies are not intrinsically positive for environmental sustainability. Through the literature analysis, it was challenging to find research papers that objectively and openly covered both positive and negative implications of digital technologies on environmental sustainability. In addition, the authors found that some scholars preferred to present implications of Industry 4.0 either in a general level or focusing only on the implementation of one particular technology, as shown in Table 3. Considering this situation, the authors decided to map the digital technologies of Industry 4.0 against the 5C architecture framework [36] in order to visualize which elements have already been explored and which gaps exist to date in research in a broader and more holistic perspective. Attempting to fulfill the above-mentioned research gaps, the first posed research question was answered by looking at the digital technologies from a holistic perspective, to further synthetize both their positive and negative environmental impacts, as indicated in Table 4 and Figure 6.

Furthermore, the literature review reported an increasing trend in the number of published studies on environmental sustainability implications of digitalization (Figure 3), but recent studies still show that companies prioritize economic opportunities of Industry 4.0 over environmental and social gains [14,72]. Thus, this study aims to highlight that, although digitalization has demonstrated support to productivity in manufacturing environments, it could also support the reduction of environmental impact. The analysis and summary of industrial practices in using digital technologies to reduce environmental impacts, as illustrated in Table 4, formulating the answers to the second research question.

Based on the findings, the following sections will discuss (i) the perspective of both product and technology lifecycles, (ii) implications from the interconnection within the Triple Bottom Line (TBL), (iii) implications to researchers, (iv) implications to practitioners, and (v) outlook and limitations of the study.

4.1. The Lifecycle Perspective

The rapid development of digitalization, especially in the context of Industry 4.0, motivates manufacturing industries to speed up their digital transformation. This brings massive opportunities to manufacturers to improve the operational performance; but meanwhile, it introduces undesirable environmental impacts. However, manufacturing industries generally focus on the product's lifecycle, and so do most scholars in academia. Thus, the model presented below aims to provide a perspective that includes both product and technology lifecycles (see Figure 6).

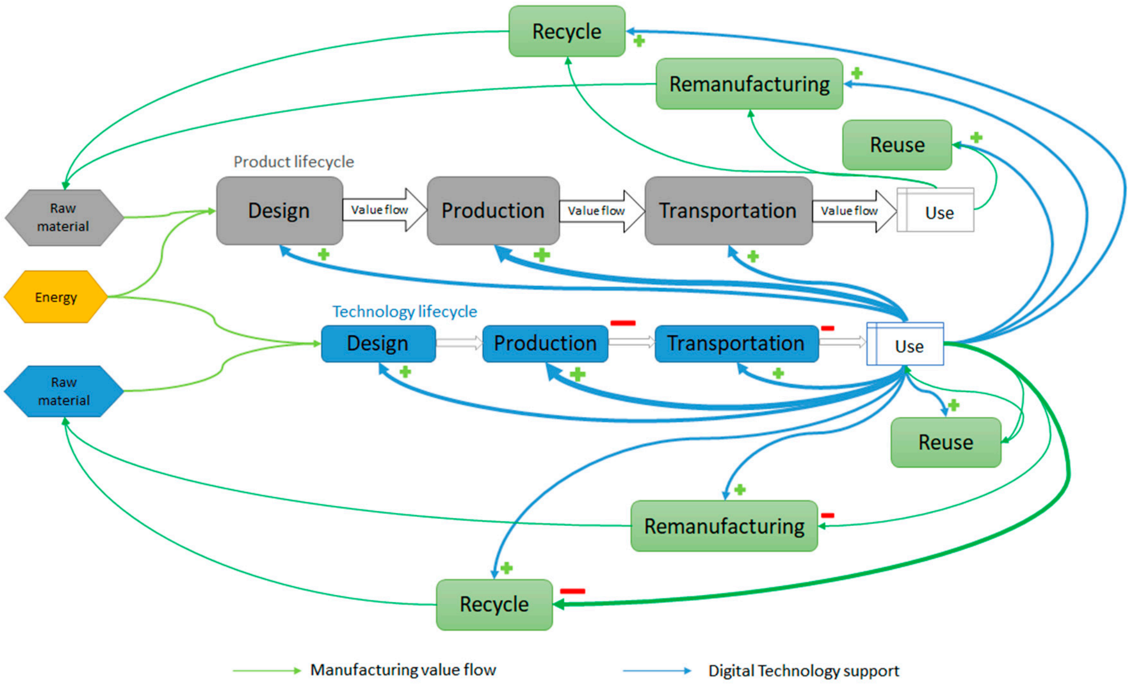

Figure 6. Value chain of product lifecycle and technology lifecycle.

As shown with the Entity Relationship Diagram in Figure 6, the product lifecycle is illustrated in grey in the upper part, while the technology cycle is illustrated in blue in the lower part. In the product lifecycle, material and energy are the main inputs from the left side (in the diagram); value flows through the product lifecycle, and goes onto the right with manufactured product. The end-of-life product could re-enter the value creation cycle through reuse, remanufacturing, recycling, and other circular strategies. In the technology lifecycle, energy and material as inputs from the left (in the diagram) go through its value creation and come out as technology hardware. This technology hardware supports each value creation process in the product lifecycle, where it contributes to increased efficiency and quality, amongst other benefits. This hardware could also re-enter the value creation cycle through similar circular strategies.

In the product lifecycle (shown in the upper part of the Figure 6), digital technologies enable environmental impact reduction mainly with high material efficiency and information support in manufacturing, which is represented with the green plus sign. With the purpose of increasing efficiency, environmental impact reduction could happen by implementing digitalization at each stage of both product and technology lifecycles. From the studied literature, this implementation mainly happens at the *production* stage, as summarized in Table 4. Nevertheless, the technology lifecycle (shown in the lower part of the Figure 6) leads to a high consumption of energy and resources and an increase of total emissions, represented with the red minus sign. This negative impact is mostly generated from the *production* and the *end-of-life* of technology hardware in the technology lifecycle, as described in Table 5. As Nascimento et al. (2019) stated, Industry 4.0 is supported by the development of ICTs [3]; the negative impact originates mainly from the *production* and the *end-of-life* of ICTs. Therefore, studies on green and/or sustainable ICTs are of vital importance to enable overall environmental benefits [126,129].

4.2. Implications from the Interconnection within the TBL

Visualizing energy flows does not automatically lead to energy savings and waste reduction [90]. The data monitored through IoT and CPS itself does not lead to a reduction of energy or resource consumption. Similarly, awareness of the overall implications does not automatically lead to decisions that optimize operational performance towards sustainability. The availability of data and the access to data collection, enabled by digital technologies, provide decision makers with relevant information and can deepen their understanding of the complex business environment. It is the responsibility of decision makers to find the balance between economic and environmental benefits. As Glavič and Lukman (2007) state, environmental sustainability is primarily concerned with maintaining "the balance of natural resource consumption and replenishment, and ecological integrity" [19]. Companies need to prioritize environmental sustainability in their strategy and decision-making processes, because environmental impact data and information only create value when used with the intent to reduce the ecological cost of their business activities.

As shown in Table 3, the three pillars of sustainability are interconnected. Although this study focuses on environmental sustainability, it is important to acknowledge the other two pillars when it comes to the impact of digitalization. Overall, it could be argued that environmental benefits can be aligned to economic sustainability benefits easier than to social sustainability, as more papers are showing correlations between the first two mentioned pillars. This phenomenon can be explained from the lean–green [53,78] and resource and energy efficiency perspectives [9,77,80]. Lean–green management has been introduced as an effective way to improve environmental and economic efficiency in manufacturing [130], because the principle of eliminating waste from lean has mainly positive impacts on improving environmental performance [53]. The resource and energy efficiency can be related to the circular economy, a mindset that manufacturing industries tend to adopt to reintroduce waste as raw material and transform their business into circular chains [3,130,131]. It can also be related with less consumption of energy and/or resource from more efficient production and delivery [106,117,132].

From the studied literature, Industry 4.0 offers opportunities by removing repetitive tasks, alleviating heavy workload, and increasing productivity and convenience [24,72], but it also brings challenges, such as decreased employment, information security issues, and data complexity [24,65]. Furthermore, it raises the requirements for producers and consumers with implications on corporate social responsibility throughout the life cycle of a product [24]. Impacts on social sustainability seem to be more difficult to understand and measure in comparison to environmental or economic impacts; this is usually addressed by processing feedback from individuals on customer satisfaction [24]. However, economic benefits are caused by social efforts and activities; environmental benefits can result in increased attractiveness for investors, better image, and quality, leading to an easier economic success [27].

This interconnection between the three pillars of sustainability calls for a better understanding of the profound impacts of digitalization from different perspectives. For instance, the use of intelligent robotics requires intensive energy supply, which generates negative impact on the environment. However, the use of robotics alleviates heavy workload and performs non-ergonomic tasks for operators, which generates a positive social impact [3]. Furthermore, robots could replace the workforce with higher flexibility and stable quality [111]. Another example can be found in data transparency: it enables communication throughout the lifecycle, but also brings challenges in terms of cyber security [74].

4.3. Implications to Researchers

A major part of the studied literature focuses on the application of digitalization in product lifecycle. CPS, connection level technologies, and AM from the conversion level are mostly implemented and studied to reduce environmental impact. Meanwhile, intelligent robotics and other technologies from the cyber, cognition, and configuration levels of the 5C architecture need further exploration, especially at the design, transportation, use, and end-of-life stages. This does not necessarily show a lack of studies on the application of technology itself, but it highlights a lack of studies that address the potential to reduce environmental impact in manufacturing.

Technology lifecycle is less addressed in literature in comparison with product lifecycle. The implementation of digital technologies, especially connectivity, enable higher resource and information efficiency, which contribute to environmental sustainability. The negative impact, which is mainly from the lifecycle of technology hardware, indicates the need for more extensive studies.

Figure 6 provides an overview of both positive and negative impacts by illustrating the product and technology lifecycles. A possible starting point could be to map each technology's overall implications for the environment, exploring and assessing the environmental impact of the application of technology in manufacturing and the lifecycle of the technology hardware.

"Sustainability actions should be regarded in combination rather than in isolation" [27]. From the mapping and analysis of economic and social pillars in Table 3, it seems that each of the three elements of the TBL cannot be isolated from each other. When intending to reduce environmental impact, the other two pillars shall also be considered. This is particularly relevant when introducing new technologies, as incorporating sustainability from all three dimensions could provide a better balance.

4.4. Implications to Practitioners

The interconnection within the pillars of the TBL highlights that sustainability needs to be incorporated within an entire organization and its strategy [27,133]. Table 3 also shows that the other two pillars are highly relevant when discussing environmental sustainability. Practitioners could have more confidence in the positive relationship between the three pillars, especially from green–lean integration. The potential to eliminate waste as a way of achieving increased eco-efficiency could provide an easier starting point towards sustainability.

Figure 6 provides a perspective that could support manufacturing companies, especially decision makers, to consider multiple lifecycles for the manufactured product and the digital technology implemented. It can further help manufacturers by bringing a broader picture with new opportunities for more sustainable value and avoid undesirable (and often overlooked) negative side effects of new technology implementation, leading to decisions both economically and environmentally sound.

The practices summarized from literatures in Table 4 could provide some reference for practitioners on how and where to implement digital technologies to reduce environmental impact. The practices from the connection level could indicate the possible "low hanging fruits" by tracking and optimizing resource consumption, as well as supporting efficient communication between different processes throughout the product lifecycle. Table 5, on the other hand, could remind manufacturers of the possible negative impact brought from technology itself, raising their awareness of social responsibility, as either the producer or consumer.

Digitalization has great potential to accelerate manufacturing efficiency, driving the manufacturing industry to invest in digital technologies, such as installing sensors on equipment, building IoT and CPS platforms, and collecting large amounts of data. It seems that a large number of companies are willing to collect data, but not all of them understand how to use it to create sustainable value. A study from IBM estimates that 90% of all data stored is never used [95]. This suggests that the energy used by data servers is not paid back through productive use of this collected and stored data. Manufacturers need to consider carefully which data is needed before they invest in digitalization.

According to Ehrlich and Holdren (1971), the IPAT equation can describe the impact of human activity on the environment: $I = P \times A \times T$ [134] (where I stands for environmental Impact, P stands for

Population, A is Affluence, and T is Technology). For manufacturing companies, since population and affluence are not in their control, technology is the driving force to reduce our society's environmental impact [32]. The development of digitalization, especially in the context of Industry 4.0, brings new challenges to understand and harness this new generation of technologies. With the findings presented in this study, we aim to contribute to a better understanding of the environmental impacts of digitalization from both the product and technology lifecycles. The practices identified to reduce the environmental impact of digitalization in manufacturing are presented in the summary of literature in Table 4. This summary can act as a reference guide for manufacturing practitioners, while the summary from Table 5**.** intends to alert them of the potential negative environmental impacts when adopting new digital technologies.

In summary, the results from the literature review deepen the scientific knowledge on the implications of digitalization on environmental sustainability, providing both researchers and practitioners with a holistic view of the product and technology lifecycles by aligning the eight digital technologies with the 5C architecture.

4.5. Outlook and Limitations of the Study

Considering that these findings are based on a literature study, they are mainly theoretical, and their usefulness needs to be verified through case studies, preferably with a quantitative approach. By introducing the proposed perspective, manufacturing companies can deepen their understanding of the environmental impact of digitalization in both the product and technology lifecycles. The summary of positive and negative environmental impacts needs further enrichment with practical findings. Moreover, the proposed alignment of the eight digital technologies to the adapted 5C architecture could be further developed and verified through case studies. Future work could also include further developing the multiple lifecycles perspective into a model, which shall prescribe detailed guidelines for its use as part of the digitalization process in manufacturing.

One of the limitations of this study could be that the publications after July 2020 are not included, as there might be other highly relevant articles published afterwards. Hence, the results of this research shall be validated by further studies, with a constant review of this topic. The qualitative approach of this analysis could also be a limitation of this study, as some results need further quantitative validation, such as the actual impact on environment and the extent of technology use required to achieve a reduction on environmental impacts.

5. Conclusions

Digitalization plays an increasingly important role in evolving manufacturing towards environmental sustainability. This study found a major challenge in finding articles that objectively presented both positive and negative implications of digital technologies on environmental sustainability. The implications of Industry 4.0 were usually presented either on a general level or focusing on one particular technology, lacking a holistic view. Furthermore, very few studies analyzed and summarized industrial practices for reducing environmental impact with the support of digitalization throughout manufacturing value chains.

To fulfill the mentioned gaps and expand the scientific knowledge on the implications of digitalization on environmental sustainability, this study conducted an extensive literature review, which identifies four main contributions.

First, the authors provide a synthesis of the overall environmental impact of digitalization, including both positive and negative impacts throughout the manufacturing value creation processes. Secondly, a lifecycle perspective is proposed considering the environmental impacts from both the product and technology lifecycles. In the manufactured product lifecycle, digital technologies enable environmental impact reduction mainly through high material efficiency and information support at the production stage. The technology lifecycle leads to a high consumption of energy and resources and increased emissions, mostly at the production and the end-of-life stages. The proposed perspective could help practitioners to reposition themselves as producers and/or consumers and to consider both positive and negative environmental impacts of digitalization at different stages of these two lifecycles.

Thirdly, this study provides a summary of implementation practices for industrial practitioners to better harness digital technologies in an environmentally friendly manner. This summary indicates how and where to implement digital technologies to reduce environmental impacts, especially from the connection level of the 5C architecture by tracking and optimizing resource consumption and efficient communication between different processes throughout the product lifecycle. Furthermore, the proposed alignment of the eight digital technologies to the adapted 5C architecture shows CPS, connection level technologies, and AM from the conversion level are mostly implemented and studied to reduce environmental impact. It also highlights a need for studies that address the environmental impact potential of cyber, cognition, and configuration levels of the 5C architecture.

Finally, the interconnection within the TBL identified from the studied literature could provide practitioners with more confidence on the positive relationship between the three pillars, especially from the green–lean integration [55,80,130], highlighting that introducing digital technologies to improve efficiency and productivity towards economic sustainability does not necessarily conflict with environmental sustainability. Understanding the interconnection within the TBL can support practitioners to expand the use of digitalization as means to increase the environmental sustainability of the manufacturing industry, thereby achieving more sustainable manufacturing.

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References

1. Chen, X.; Despeisse, M.; Johansson, B. Environmental impact assessment in manufacturing industry: A literature review. In Proceedings of the 6th International EurOMA Sustainable Operations and Supply Chains Forum, Gothenburg, Sweden, 18–19 March 2019.
2. IEA—International Energy Agency. *World Energy Outlook*; IEA/Organization for Economic Connection and Development (OCED): Paris, France, 2015.
3. Nascimento, D.L.M.; Alencastro, V.; Quelhas, O.L.G.; Caiado, R.G.G.; Garza-Reyes, J.A.; Rocha-Lona, L.; Tortorella, G. Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context: A business model proposal. *J. Manuf. Technol. Manag.* **2019**, *30*, 607–627. [CrossRef]
4. de Sousa Jabbour, A.B.L.; Jabbour, C.J.C.; Foropon, C.; Godinho Filho, M. When titans meet—Can industry 4.0 revolutionise the environmentally-sustainable manufacturing wave? The role of critical success factors. *Technol. Soc. Chang.* **2018**, *132*, 18–25. [CrossRef]
5. Carvalho, S.; Cosgrove, J.; Rezende, J.; Doyle, F. Machine level energy data analysis—Development and validation of a machine learning based tool. *ECEEE Ind. Summer Study Proc.* **2018**, 477–486.
6. Oláh, J.; Aburumman, N.; Popp, J.; Khan, M.A.; Haddad, H.; Kitukutha, N. Impact of Industry 4.0 on Environmental Sustainability. *Sustainability* **2020**, *12*, 4674. [CrossRef]
7. Merdin, D.; Ersoz, F. Evaluation of The Applicability of Industry 4.0 Processes in Businesses and Supply Chain Applications. In Proceedings of the 2019 3rd International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT), Ankara, Turkey, 11–13 October 2019; IEEE: Ankara, Turkey, 2019; pp. 1–10. Available online: https://doi.org/10.1109/ISMSIT.2019.8932830 (accessed on 12 September 2020).
8. Ang, J.; Goh, C.; Saldivar, A.; Li, Y. Energy-Efficient Through-Life Smart Design, Manufacturing and Operation of Ships in an Industry 4.0 Environment. *Energies* **2017**, *10*, 610. [CrossRef]

9. Lins, T.; Rabelo Oliveira, R.A. Energy efficiency in industry 4.0 using SDN. In Proceedings of the 2017 IEEE 15th International Conference on Industrial Informatics (INDIN), Emden, Germany, 24–26 July 2017; IEEE: Emden, Germany, 2017; pp. 609–614. Available online: https://doi.org/10.1109/INDIN.2017.8104841 (accessed on 12 September 2020).
10. Mehrpouya, M.; Dehghanghadikolaei, A.; Fotovvati, B.; Vosooghnia, A.; Emamian, S.S.; Gisario, A. The Potential of Additive Manufacturing in the Smart Factory Industrial 4.0: A Review. *Appl. Sci.* **2019**, *9*, 3865. [CrossRef]
11. Ford, S.; Despeisse, M. Additive manufacturing and sustainability: An exploratory study of the advantages and challenges. *J. Clean. Prod.* **2016**, *137*, 1573–1587. [CrossRef]
12. Song, Z.; Moon, Y. Assessing sustainability benefits of cybermanufacturing systems. *Int. J. Adv. Manuf. Technol.* **2017**, *90*, 1365–1382. [CrossRef]
13. Thiede, S. Environmental Sustainability of Cyber Physical Production Systems. *Procedia CIRP* **2018**, *69*, 644–649. [CrossRef]
14. Brozzi, R.; Forti, D.; Rauch, E.; Matt, D.T. The Advantages of Industry 4.0 Applications for Sustainability: Results from a Sample of Manufacturing Companies. *Sustainability* **2020**, *12*, 3647. [CrossRef]
15. Berkhout, F.; Hertin, J. De-materialising and re-materialising: Digital technologies and the environment. *Futures.* **2004**, *36*, 903–920. [CrossRef]
16. Kopp, T.; Lange, S. The Climate Effect of Digitalization in Production and Consumption in OECD Countries. *Ceur. Workshop Proc.* **2019**, *2382*, 1–11.
17. Cosar, M. Carbon footprint in data centre: A case study. *Feb. Fresenius Environ. Bull.* **2019**, 600.
18. Keeble, B.R. The Brundtland report: 'Our common future'. *Med. War* **1988**, *4*, 17–25. [CrossRef]
19. Glavič, P.; Lukman, R. Review of sustainability terms and their definitions. *J. Clean. Prod.* **2007**, *15*, 1875–1885. [CrossRef]
20. Goodland, R. The concept of environmental sustainability. *Annu. Rev. Ecol. Syst.* **1995**, *26*, 1–24. [CrossRef]
21. Morelli, J. Environmental Sustainability: A Definition for Environmental Professionals. *J. Environ. Sustain.* **2011**, *1*, 1–10. [CrossRef]
22. Malshe, H.; Nagarajan, H.; Pan, Y.; Haapala, K. Profile of Sustainability in Additive Manufacturing and Environmental Assessment of a Novel Stereolithography Process. *Int. Manuf. Sci. Eng. Conf.* **2015**. [CrossRef]
23. Rosen, M.A.; Kishawy, H.A. Sustainable Manufacturing and Design: Concepts, Practices and Needs. *Sustainability* **2012**, *4*, 154–174. [CrossRef]
24. Sartal, A.; Bellas, R.; Mejías, A.M.; García-Collado, A. The sustainable manufacturing concept, evolution and opportunities within Industry 4.0: A literature review. *Adv. Mech. Eng.* **2020**, *12*. [CrossRef]
25. Joung, C.B.; Carrell, J.; Sarkar, P.; Feng, S.C. Categorization of indicators for sustainable manufacturing. *Ecol. Indic.* **2013**, *24*, 148–157. [CrossRef]
26. Haapala, K.R.; Zhao, F.; Camelio, J.; Sutherland, J.W.; Skerlos, S.J.; Dornfeld, D.A.; Jawahir, I.S.; Clarens, A.F.; Rickli, J.L. A Review of Engineering Research in Sustainable Manufacturing. *J. Manuf. Sci. Eng.* **2013**, *135*, 041013. [CrossRef]
27. Kiel, D.; Müller, J.M.; Arnold CVoigt, K.I. Sustainable industrial value creation: Benefits and challenges of industry 4.0. *Int. J. Innov. Manag.* **2017**, *21*, 1740015. [CrossRef]
28. Margherita, E.G.; Braccini, A.M. Industry 4.0 Technologies in Flexible Manufacturing for Sustainable Organizational Value: Reflections from a Multiple Case Study of Italian Manufacturers. *Inf. Syst. Front.* **2020**. [CrossRef]
29. O'Brien, C. Sustainable production—A new paradigm for a new millennium. *Int. J. Prod. Econ.* **1999**, *60*, 1–7. [CrossRef]
30. Alayón, C.; Säfsten, K.; Johansson, G. Conceptual sustainable production principles in practice: Do they reflect what companies do? *J. Clean. Prod.* **2017**, *141*, 693–701. [CrossRef]
31. Jawahir, I.S.; Bradley, R. Technological Elements of Circular Economy and the Principles of 6R-Based Closed-loop Material Flow in Sustainable Manufacturing. *Procedia CIRP* **2016**, *40*, 103–108. [CrossRef]
32. Sarkis, J. Manufacturing's role in corporate environmental sustainability—Concerns for the new millennium. *Int. J. Oper. Prod. Manag.* **2001**, *21*, 666–686. [CrossRef]
33. Arushanyan, Y.; Ekener-Petersen, E.; Finnveden, G. Lessons learned—Review of LCAs for ICT products and services. *Comput. Ind.* **2014**, *65*, 211–234. [CrossRef]

34. Legner, C.; Eymann, T.; Hess, T.; Matt, C.; Böhmann, T.; Drews, P.; Mädche, A.; Urbach, N.; Ahlemann, F. Digitalization: Opportunity and Challenge for the Business and Information Systems Engineering Community. *Bus. Inf. Syst. Eng.* **2017**, *59*, 301–308. [CrossRef]
35. Yoo, Y.; Lyytinen, K.; Thummadi, V.; Weiss, A. Unbounded Innovation with Digitalization: A Case of Digital Camera. In Proceedings of the Annual Meeting of the Academy of Management Montréal, Montréal, QC, Canada, 6–10 August 2010; pp. 1–41.
36. Lee, J.; Bagheri, B.; Kao, H. A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. *Manuf. Lett.* **2015**, *3*, 18–23. [CrossRef]
37. Wang, Y. Cognitive Robots. *IEEE Robot. Autom. Mag.* **2010**, *17*, 54–62. [CrossRef]
38. Frazier, W.E. Metal additive manufacturing: A review. *J. Mater. Eng. Perform.* **2014**, *23*, 1917–1928. [CrossRef]
39. Gandomi, A.; Haider, M. Beyond the hype: Big data concepts, methods, and analytics. *Int. J. Inf. Manag.* **2015**, *35*, 137–144. [CrossRef]
40. Mell, P.; Grance, T. *The NIST Definition of Cloud Computing*; Special publication 800-145; National Institute of Standards and Technology: Gaithersburg, MD, USA, 2011.
41. Latta, J.N.; Oberg, D.J. A conceptual virtual reality model. *IEEE Comput. Grap Appl.* **1994**, *14*, 23–29. [CrossRef]
42. Lee, J. Definition and Meaning of Industrial AI. In *Industrial AI*; Springer: Singapore, 2020. Available online: https://doi.org/10.1007/978-981-15-2144-7_3 (accessed on 12 September 2020).
43. International Telecommunication Union. *Overview of the Internet of Things. Global Information Infrastructure, Internet Protocol Aspects and Next-Generation Networks*; ITU: Geneva, Switzerland, 2012.
44. Tilson, D.; Lyytinen, K.; Sørensen, C. Digital Infrastructures: The Missing IS Research Agenda. *Inf. Syst. Res.* **2010**, *21*, 748–759. [CrossRef]
45. Rüßmann, M.; Lorenz, M.; Gerbert, P.; Waldner, M.; Justus, J.; Engel, P.; Harnisch, M. *Industry 4.0: The Future of Productivity and Growth in Manufacturing*; Boston Consulting Group: Boston, MA, USA, 2015.
46. ASTM. *ASTM F2792-12a: Standard Terminology for Additive Manufacturing Technologies*; ASTM International: West Conshohocken, PA, USA, 2012.
47. Monzón, M.D.; Ortega, Z.; Martínez, A.; Ortega, F. Standardization in additive manufacturing: Activities carried out by international organizations and projects. *Int. J. Adv. Manuf. Technol.* **2015**, *76*, 1111–1121. [CrossRef]
48. Gartner, I.T. Glossary. 2020. Available online: http://www.gartner.com/it-glossary/big-data/ (accessed on 12 September 2020).
49. Monostori, L.; Kádár, B.; Bauernhansl, T.; Kondoh, S.; Kumara, S.; Reinhart, G.; Sauer, O.; Schuh, G.; Sihn, W.; Ueda, K. Cyber-physical systems in manufacturing. *Cirp Ann.* **2016**, *65*, 621–641. [CrossRef]
50. Mashhadi, A.R.; Behdad, S. Ubiquitous Life Cycle Assessment (U-LCA): A Proposed Concept for Environmental and Social Impact Assessment of Industry 4.0. *Manuf. Lett.* **2018**, *15*, 93–96. [CrossRef]
51. Stock, T.; Seliger, G. Opportunities of Sustainable Manufacturing in Industry 4.0. *Procedia CIRP.* **2016**, *40*, 536–541. [CrossRef]
52. Berkhout, F.; Hertin, J. *Impacts of Information and Communication Technologies on Environmental Sustainability: Speculations and Evidence*; OECD: Brighton, UK, 2001.
53. Santos, J.; Muñoz-Villamizar, A.; Ormazábal, M.; Viles, E. Using problem-oriented monitoring to simultaneously improve productivity and environmental performance in manufacturing companies. *Int. J. Comput. Integr. Manuf.* **2019**, *32*, 183–193. [CrossRef]
54. Zhang, W.; Gu, F.; Guo, J. Can smart factories bring environmental benefits to their products? A case study of household refrigerators. *J. Ind. Ecol.* **2019**, *23*, 1381–1395. [CrossRef]
55. Ghobakhloo, M. Industry 4.0, digitization, and opportunities for sustainability. *J. Clean. Prod.* **2020**, *252*, 119869. [CrossRef]
56. Chang, M.M.L.; Ong, S.K.; Nee, A.Y.C. Approaches and Challenges in Product Disassembly Planning for Sustainability. *Procedia Cirp.* **2017**, *60*, 506–511. [CrossRef]
57. Junior, J.A.G.; Busso, C.M.; Gobbo, S.C.O.; Carreão, H. Making the links among environmental protection, process safety, and industry 4.0. *Process. Saf. Env. Prot.* **2018**, *117*, 372–382. [CrossRef]
58. Chiarini, A.; Belvedere, V.; Grando, A. Industry 4.0 strategies and technological developments. An exploratory research from Italian manufacturing companies. *Prod. Plan. Control* **2020**, *6*, 1–14. [CrossRef]

59. Williams, E. Environmental effects of information and communications technologies. *Nature* **2011**, *479*, 354–358. [CrossRef]
60. Nnorom, I.C.; Osibanjo, O. Overview of electronic waste (e-waste) management practices and legislations, and their poor applications in the developing countries. *Resour. Conserv. Recycl.* **2008**, *52*, 843–858. [CrossRef]
61. Karlsson, C. *Research Methods for Operations Management*, 2nd ed.; Routledge: New York, NY, USA, 2016; p. 336. [CrossRef]
62. Hart, C. *Doing a Literature Review: Releasing the Research Imagination*; Sage Publications Ltd: London, UK, 2018.
63. Chen, P.P.S. The entity-relationship model—Toward a unified view of data. *ACM Trans. Database Syst. (TODS)* **1976**, *1*, 9–36. [CrossRef]
64. Dev, N.K.; Shankar, R.; Qaiser, F.H. Industry 4.0 and circular economy: Operational excellence for sustainable reverse supply chain performance. *Resour. Conserv. Recycl.* **2020**, *153*, 104583. [CrossRef]
65. Bai, C.; Dallasega, P.; Orzes, G.; Sarkis, J. Industry 4.0 technologies assessment: A sustainability perspective. *Int. J. Prod. Econ.* **2020**, *229*, 107776. [CrossRef]
66. Výtisk, J.; Kočí, V.; Honus, S.; Vrtek, M. Current options in the life cycle assessment of additive manufacturing products. *Open Eng.* **2019**, *9*, 674–682. [CrossRef]
67. Tozanlı, Ö.; Kongar, E.; Gupta, S.M. Trade-in-to-upgrade as a marketing strategy in disassembly-to-order systems at the edge of blockchain technology. *Int. J. Prod. Res.* **2020**, 1–18. [CrossRef]
68. Arnal, Á.J.; Díaz-Ramírez, M.; Acevedo, L.; Ferreira, V.J.; García-Armingol, T.; López-Sabirón, A.M.; Ferreira, G. Multicriteria Analysis for Retrofitting of Natural Gas Melting and Heating Furnaces for Sustainable Manufacturing and Industry 4.0. *J. Energy Resour. Technol.* **2020**, *142*, 022203. [CrossRef]
69. Jayakumar, J.; Jayakrishna, K.; Vimal, K.E.K.; Hasibuan, S. Modelling of sharing networks in the circular economy. *J. Model. Manag.* **2020**. [CrossRef]
70. Mourtzis, D.; Zervas, E.; Boli, N.; Pittaro, P. A cloud-based resource planning tool for the production and installation of industrial product service systems (IPSS). *Int. J. Adv. Manuf. Technol.* **2020**, *106*, 4945–4963. [CrossRef]
71. Hannula, J.; Godinho, J.R.A.; Llamas, A.A.; Luukkanen, S.; Reuter, M.A. Simulation-Based Exergy and LCA Analysis of Aluminum Recycling: Linking Predictive Physical Separation and Re-melting Process Models with Specific Alloy Production. *J. Sustain. Met.* **2020**, *6*, 174–189. [CrossRef]
72. García-Muiña, F.E.; Medina-Salgado, M.S.; Ferrari, A.M.; Cucchi, M. Sustainability Transition in Industry 4.0 and Smart Manufacturing with the Triple-Layered Business Model Canvas. *Sustainability* **2020**, *12*, 2364. [CrossRef]
73. Inderwildi, O.; Zhang, C.; Wang, X.; Kraft, M. The impact of intelligent cyber-physical systems on the decarbonization of energy. *Energy Environ. Sci.* **2020**, *13*, 744–771. [CrossRef]
74. Lucivero, F. Big data, big waste? A reflection on the environmental sustainability of big data initiatives. *Sci. Eng. Ethics* **2020**, *26*, 1009–1030. [CrossRef]
75. Jena, M.C.; Mishra, S.K.; Moharana, H.S. Application of Industry 4.0 to enhance sustainable manufacturing. *Environ. Prog. Sustain. Energy* **2020**, *39*, 13360. [CrossRef]
76. Fisher, O.J.; Watson, N.J.; Escrig, J.E.; Gomes, R.L. Intelligent Resource Use to Deliver Waste Valorisation and Process Resilience in Manufacturing Environments. *Johns. Matthey Technol. Rev.* **2020**, 64. [CrossRef]
77. Gan, V.J.; Lo, I.M.; Ma, J.; Tse, K.T.; Cheng, J.C.; Chan, C.M. Simulation optimisation towards energy efficient green buildings: Current status and future trends. *J. Clean. Prod.* **2020**, *254*, 120012. [CrossRef]
78. Ghobakhloo, M.; Fathi, M. Corporate survival in Industry 4.0 era: The enabling role of lean-digitized manufacturing. *J. Manuf. Technol. Manag.* **2019**. [CrossRef]
79. Kerin, M.; Pham, D.T. A review of emerging industry 4.0 technologies in remanufacturing. *J. Clean. Prod.* **2019**, *237*, 117805. [CrossRef]
80. Bonfá, F.; Benedetti, M.; Ubertini, S.; Introna, V.; Santolamazza, A. New efficiency opportunities arising from intelligent real time control tools applications: The case of Compressed Air Systems' energy efficiency in production and use. *Energy Procedia* **2019**, *158*, 4198–4203. [CrossRef]
81. Supekar, S.D.; Graziano, D.J.; Riddle, M.E.; Nimbalkar, S.U.; Das, S.; Shehabi, A.; Cresko, J. A Framework for Quantifying Energy and Productivity Benefits of Smart Manufacturing Technologies. *Procedia CIRP* **2019**, *80*, 699–704. [CrossRef]

82. Mele, M.; Campana, G.; D'Avino, G. A Life-Cycle Assessment Framework for Stereolithography. In *International Conference on Sustainable Design and Manufacturing*; Springer: Singapore, 2019; pp. 91–100. [CrossRef]
83. Saudi, M.H.M.; Sinaga, O.; Roespinoedji, D.; Razimi, M.S.A. Environmental Sustainability in the Fourth Industrial Revolution: The Nexus between Green Product and Green Process Innovation. *Int. J. Energy Econ. Policy* **2019**, *9*, 363. [CrossRef]
84. Sinaga, O.; Saudi, M.H.M.; Roespinoedji, D.; Razimi, M.S.A. The Dynamic Nexus of Digital Evolution, Environmental Turbulence and Environmental Performance: A Case of High-tech Industries in the Emerging 4th Industrial Revolution. *Int. J. Energy Econ. Policy* **2019**, *9*, 386–393. [CrossRef]
85. Annibaldi, V.; Rotilio, M. Energy consumption consideration of 3D printing. In Proceedings of the 2019 II Workshop on Metrology for Industry 4.0 and IoT (MetroInd4. 0&IoT), Naples, Italy, 4–6 June 2019; pp. 243–248. [CrossRef]
86. Ojo, O.O.; Zigan, S.; Orchard, J.; Shah, S. Advanced Technology Integration in Food Manufacturing Supply Chain Environment: Pathway to Sustainability and Companies' Prosperity. In Proceedings of the 2019 IEEE Technology & Engineering Management Conference (TEMSCON), Atlanta, GA, USA, 12–14 June 2019; pp. 1–7. [CrossRef]
87. Naderi, M.; Ares, E.; Peláez, G.; Prieto, D.; Araújo, M. Sustainable Operations Management for Industry 4.0 and its Social Return. *IFAC-PapersOnLine* **2019**, *52*, 457–462. [CrossRef]
88. Schischke, K.; Manessis, D.; Pawlikowski, J.; Kupka, T.; Krivec, T.; Pamminger, R.; Glaser, S.; Podhradsky, G.; Nissen, N.F.; Schneider-Ramelow, M.; et al. Embedding as a key Board-Level Technology for Modularization and Circular Design of Smart Mobile Products: Environmental Assessment. In Proceedings of the 2019 22nd European Microelectronics and Packaging Conference & Exhibition (EMPC), Pisa, Italy, 16–19 September 2019; pp. 1–8.
89. Jagtap, S.; Rahimifard, S. The digitisation of food manufacturing to reduce waste–Case study of a ready meal factory. *Waste Manag.* **2019**, *87*, 387–397. [CrossRef] [PubMed]
90. Sénéchal, O.; Trentesaux, D. A framework to help decision makers to be environmentally aware during the maintenance of cyber physical systems. *Environ. Impact Assess. Rev.* **2019**, *77*, 11–22. [CrossRef]
91. Asadi, S.; Nilashi, M.; Safaei, M.; Abdullah, R.; Saeed, F.; Yadegaridehkordi, E.; Samad, S. Investigating factors influencing decision-makers' intention to adopt Green IT in Malaysian manufacturing industry. *Resour. Conserv. Recycl.* **2019**, *148*, 36–54. [CrossRef]
92. Garcia, D.J.; Mozaffar, M.; Ren, H.; Correa, J.E.; Ehmann, K.; Cao, J.; You, F. Sustainable manufacturing with cyber-physical discrete manufacturing networks: Overview and modeling framework. *J. Manuf. Sci. Eng.* **2019**, 141. [CrossRef]
93. Liu, Q.; Liu, Z.; Xu, W.; Tang, Q.; Zhou, Z.; Pham, D.T. Human-robot collaboration in disassembly for sustainable manufacturing. *Int. J. Prod. Res.* **2019**, *57*, 4027–4044. [CrossRef]
94. Garcia-Muiña, F.E.; González-Sánchez, R.; Ferrari, A.M.; Volpi, L.; Pini, M.; Siligardi, C.; Settembre-Blundo, D. Identifying the equilibrium point between sustainability goals and circular economy practices in an Industry 4.0 manufacturing context using eco-design. *Soc. Sci.* **2019**, *8*, 241. [CrossRef]
95. Corbett, C.J. How sustainable is big data? *Prod. Oper. Manag.* **2018**, *27*, 1685–1695. [CrossRef]
96. Müller, J.M.; Kiel DVoigt, K.I. What drives the implementation of Industry 4.0? The role of opportunities and challenges in the context of sustainability. *Sustainability* **2018**, *10*, 247. [CrossRef]
97. de Sousa Jabbour, A.B.L.; Jabbour, C.J.C.; Godinho Filho, M.; Roubaud, D. Industry 4.0 and the circular economy: A proposed research agenda and original roadmap for sustainable operations. *Ann. Oper. Res.* **2018**, *270*, 273–286. [CrossRef]
98. Parmiggiani, E.; Monteiro, E. Shifting Baselines? Recommendations for Green IS. In Proceedings of the 39th International Conference on Information Systems (ICIS), San Francisco, CA, USA, 13–18 December 2018.
99. Lammers, T.; Tomidei, L.; Regattieri, A. What Causes Companies to Transform Digitally? An Overview of Drivers for Australian Key Industries. In Proceedings of the 2018 Portland International Conference on Management of Engineering and Technology (PICMET), Honolulu, WI, USA, 19 August 2018; pp. 1–8. [CrossRef]
100. Thomas, A.; Haven-Tang, C.; Barton, R.; Mason-Jones, R.; Francis, M.; Byard, P. Smart Systems Implementation in UK Food Manufacturing Companies: A Sustainability Perspective. *Sustainability* **2018**, *10*, 4693. [CrossRef]

101. Böhner, J.; Scholz, M.; Franke, J.; Sauer, A. Integrating digitization technologies into resource efficiency driven industrial learning environments. *Procedia Manuf.* **2018**, *23*, 39–44. [CrossRef]
102. Tucker, D.; Pezzini, P.; Bryden, K.M. Cyber-Physical Systems: A New Paradigm for Energy Technology Development. In Proceedings of the ASME 2018 Power Conference collocated with the ASME 2018 12th International Conference on Energy Sustainability and the ASME 2018 Nuclear Forum, Lake Buena Vista, FL, USA, 24–28 June 2018; American Society of Mechanical Engineers: New York, NY, USA, 2018; Volume 51395, p. V001T04A001. [CrossRef]
103. Gružauskas, V.; Baskutis, S.; Navickas, V. Minimizing the trade-off between sustainability and cost effective performance by using autonomous vehicles. *J. Clean. Prod.* **2018**, *184*, 709–717. [CrossRef]
104. Palacin-Silva, M.V.; Seffah, A.; Porras, J. Infusing sustainability into software engineering education: Lessons learned from capstone projects. *J. Clean. Prod.* **2018**, *172*, 4338–4347. [CrossRef]
105. Braccini, A.M.; Margherita, E.G. Exploring organizational sustainability of industry 4.0 under the triple bottom line: The case of a manufacturing company. *Sustainability* **2019**, *11*, 36. [CrossRef]
106. Ghafoorpoor Yazdi, P.; Azizi, A.; Hashemipour, M. An empirical investigation of the relationship between overall equipment efficiency (OEE) and manufacturing sustainability in industry 4.0 with time study approach. *Sustainability* **2018**, *10*, 3031. [CrossRef]
107. Kumar, R.; Singh, S.P.; Lamba, K. Sustainable robust layout using Big Data approach: A key towards industry 4.0. *J. Clean. Prod.* **2018**, *204*, 643–659. [CrossRef]
108. Bieser, J.C.T.; Hilty, L.M. Assessing Indirect Environmental Effects of Information and Communication Technology (ICT): A Systematic Literature Review. *Sustainability* **2018**, *10*, 2662. [CrossRef]
109. Garcia-Muiña, F.E.; González-Sánchez, R.; Ferrari, A.M.; Settembre-Blundo, D. The paradigms of Industry 4.0 and circular economy as enabling drivers for the competitiveness of businesses and territories: The case of an Italian ceramic tiles manufacturing company. *Soc. Sci.* **2018**, *7*, 255. [CrossRef]
110. Fu, B.; Shu, Z.; Liu, X. Blockchain enhanced emission trading framework in fashion apparel manufacturing industry. *Sustainability* **2018**, *10*, 1105. [CrossRef]
111. Bonilla, S.H.; Silva, H.R.; Terra da Silva, M.; Franco Gonçalves, R.; Sacomano, J.B. Industry 4.0 and sustainability implications: A scenario-based analysis of the impacts and challenges. *Sustainability* **2018**, *10*, 3740. [CrossRef]
112. Zheng, P.; Lin, T.J.; Chen, C.H.; Xu, X. A systematic design approach for service innovation of smart product-service systems. *J. Clean. Prod.* **2018**, *201*, 657–667. [CrossRef]
113. Waibel, M.W.; Steenkamp, L.P.; Moloko, N.; Oosthuizen, G.A. Investigating the effects of smart production systems on sustainability elements. *Procedia Manuf.* **2017**, *8*, 731–737. [CrossRef]
114. Prause, G.; Atari, S. On sustainable production networks for Industry 4.0. *Entrep. Sustain. Issues* **2017**, *4*, 421–431. [CrossRef]
115. Ballarino, A.; Brondi, C.; Brusaferri, A.; Chizzoli, G. The CPS and LCA modelling: An integrated approach in the environmental sustainability perspective. In *Working Conference on Virtual Enterprises*; Springer: Cham, Switzerland, 2017; pp. 543–552. [CrossRef]
116. Szalavetz, A. The Environmental Impact of Advanced Manufacturing Technologies: Examples from Hungary. In *Central European Business Review*; Prague University of Economics and Business: Prague, Czechia, 2017; pp. 18–29. [CrossRef]
117. Schlegel, A.; Langer, T.; Putz, M. Developing and harnessing the potential of SMEs for eco-efficient flexible production. *Procedia Manuf.* **2017**, *9*, 41–48. [CrossRef]
118. Bechtsis, D.; Tsolakis, N.; Vouzas, M.; Vlachos, D. Industry 4.0: Sustainable material handling processes in industrial environments. In *Computer Aided Chemical Engineering*; Elsevier: Amsterdam, The Netherlands, 2017; Volume 40, pp. 2281–2286. [CrossRef]
119. Li, A.Q.; Found, P. Towards sustainability: PSS, digital technology and value co-creation. *Procedia CIRP* **2017**, *64*, 79–84. [CrossRef]
120. Watanabe, E.H.; da Silva, R.M.; Junqueira, F.; dos Santos Filho, D.J.; Miyagi, P.E. An emerging industrial business model considering sustainability evaluation and using cyber physical system technology and modelling techniques. *IFAC-PapersOnLine* **2016**, *49*, 135–140. [CrossRef]
121. Loy, J.; Tatham, P. Redesigning Production Systems. In *Handbook of Sustainability in Additive Manufacturing. Environmental Footprints and Eco-Design of Products and Processes*; Muthu, S., Savalani, M., Eds.; Springer: Singapore, 2016. [CrossRef]

122. Griffiths, C.A.; Howarth, J.; De Almeida-Rowbotham, G.; Rees, A.; Kerton, R. A design of experiments approach for the optimisation of energy and waste during the production of parts manufactured by 3D printing. *J. Clean. Prod.* **2016**, *139*, 74–85. [CrossRef]
123. Herrmann, C.; Schmidt, C.; Kurle, D.; Blume, S.; Thiede, S. Sustainability in manufacturing and factories of the future. *Int. J. Precis. Eng. Manuf. Green Technol.* **2014**, *1*, 283–292. [CrossRef]
124. Matsuda, M.; Kimura, F. Digital Eco-factory as an IT Support Tool for Sustainable Manufacturing. In *IFIP International Conference on Digital Product and Process Development Systems*; Springer: Berlin/Heidelberg, Germany, 2013; pp. 330–342. [CrossRef]
125. Steinhilper, R.; Freiberger, S.; Kübler, F.; Böhner, J. RFID integrated adaption of manufacturing execution systems for energy efficient production. In *Re-Engineering Manufacturing for Sustainability*; Springer: Singapore, 2013; pp. 123–128. [CrossRef]
126. Sissa, G. An Agent Based approach for sustainable ICT services toward environmental sustainability: The use of Agent Based Models to explain the ICT-driven (societal) behavioural changes and their effects on environmental sustainability. In Proceedings of the 2012 6th IEEE International Conference on Digital Ecosystems and Technologies (DEST), Menlo Park, CA, USA, 18–20 June 2012; pp. 1–6. [CrossRef]
127. Howard, G.R.; Lubbe, S. Synthesis of green is frameworks for achieving strong environmental sustainability in organisations. In Proceedings of the 2012 South African Institute of Computer Scientists and Information Technologists Conference, Pretoria, South Africa, 1–3 October 2012; pp. 306–315. [CrossRef]
128. Andræ, A.S.; Zou, G.; Liu, J. LCA of electronic products. *Int. J. Life Cycle Assess.* **2004**, *9*, 45–52. [CrossRef]
129. Stock, T.; Obenaus, M.; Kunz, S.; Kohl, H. Industry 4.0 as enabler for a sustainable development: A qualitative assessment of its ecological and social potential. *Process Saf. Environ. Prot.* **2018**, *118*, 254–267. [CrossRef]
130. Kurdve, M.; Bellgran, M. Green lean operationalisation of the circular economy concept on production shop floor level. *J. Clean. Prod.* **2021**, *278*, 123–223. [CrossRef]
131. Cioffi, R.; Travaglioni, M.; Piscitelli, G.; Petrillo, A.; Parmentola, A. Smart Manufacturing Systems and Applied Industrial Technologies for a Sustainable Industry: A Systematic Literature Review. *Appl. Sci.* **2020**, *10*, 2897. [CrossRef]
132. Terry, S.; Lu, H.; Fidan, I.; Zhang, Y.; Tantawi, K.; Guo, T.; Asiabanpour, B. The Influence of Smart Manufacturing Towards Energy Conservation: A Review. *Technologies* **2020**, *8*, 31. [CrossRef]
133. Schulz, S.A.; Flanigan, R.L. Developing competitive advantage using the triple bottom line: A conceptual framework. *J. Bus. Ind. Mark.* **2016**. [CrossRef]
134. Ehrlich, P.R.; Holdren, J.P. Impact of population growth. *Science* **1971**, *171*, 1212–1217. [CrossRef] [PubMed]